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(54) **MICRO-TRANSFER PRINTING WITH SELECTIVE COMPONENT REMOVAL**

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(51) **Int. Cl.**
H01L 21/68 (2006.01)
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(Continued)

(52) **U.S. Cl.**
CPC **H01L 21/6835** (2013.01); **B29C 59/026** (2013.01); **G03F 7/0002** (2013.01);
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(58) **Field of Classification Search**
CPC H01L 21/67144; H01L 21/6835; H01L 22/20; H01L 25/0753
(Continued)

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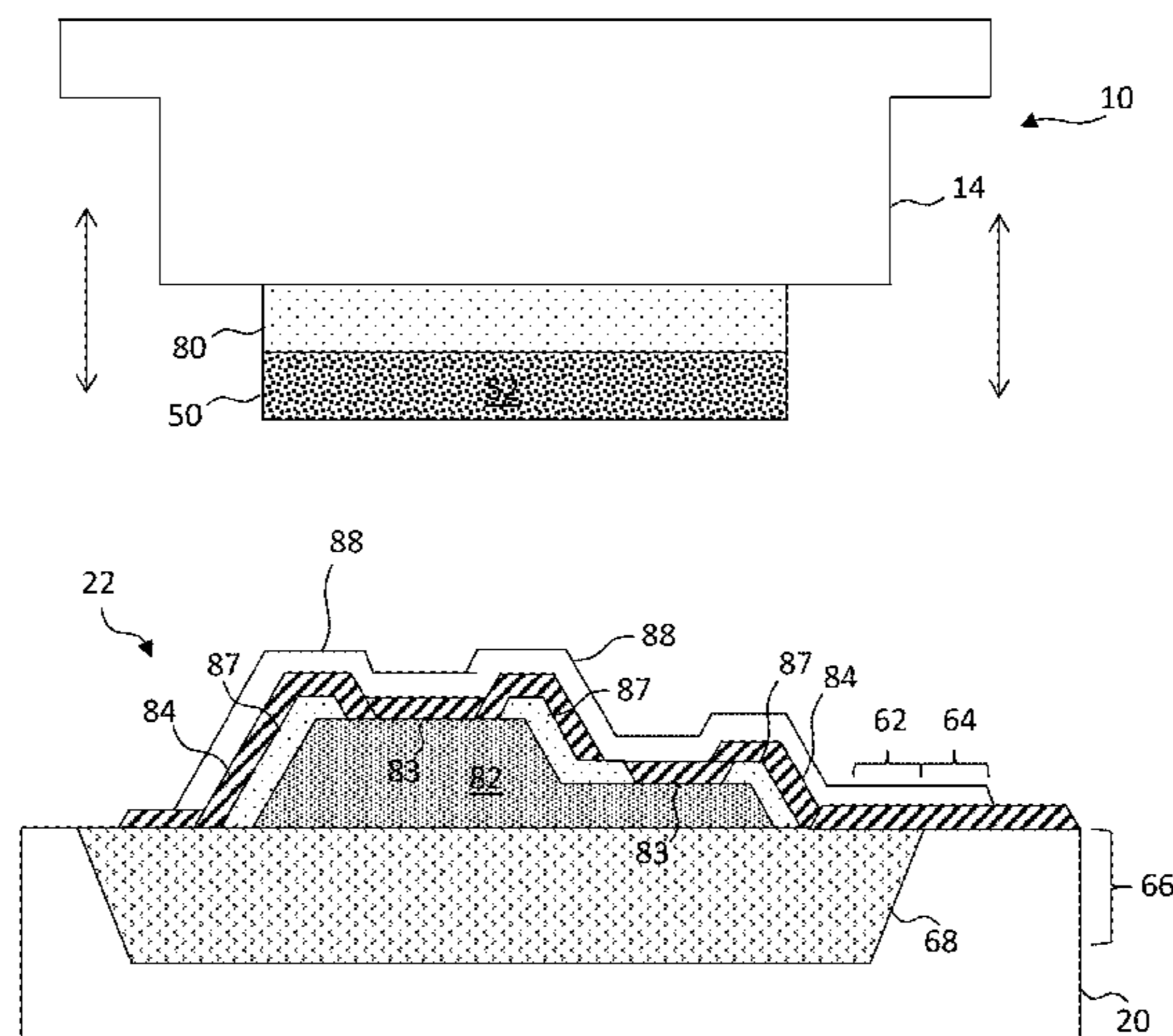
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(57) **ABSTRACT**

An example of a method of micro-transfer printing comprises providing a micro-transfer printable component source wafer, providing a stamp comprising a body and spaced-apart posts, and providing a light source for controllably irradiating each of the posts with light through the body. Each of the posts is contacted to a component to adhere the component thereto. The stamp with the adhered components is removed from the component source wafer. The selected posts are irradiated through the body with the light to detach selected components adhered to selected posts from the selected posts, leaving non-selected components adhered to non-selected posts. In some embodiments, using the stamp, the selected components are adhered to a provided destination substrate. In some embodiments, the selected components are discarded. An example micro-transfer printing system comprises a stamp comprising a body and spaced-apart posts and a light source for selectively irradiating each of the posts with light.

20 Claims, 22 Drawing Sheets



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H01L 21/56 (2006.01)
H01L 21/306 (2006.01)
H01L 23/31 (2006.01)
H01L 23/00 (2006.01)
H01L 25/00 (2006.01)
H01L 25/075 (2006.01)
G03F 7/00 (2006.01)
H05K 1/11 (2006.01)
B29C 59/02 (2006.01)

(52) **U.S. Cl.**
 CPC *H01L 21/306* (2013.01); *H01L 21/568* (2013.01); *H01L 21/7806* (2013.01); *H01L 23/3171* (2013.01); *H01L 24/24* (2013.01); *H01L 24/29* (2013.01); *H01L 24/75* (2013.01); *H01L 24/97* (2013.01); *H01L 25/0753* (2013.01); *H01L 25/50* (2013.01); *H05K 1/111* (2013.01); *H01L 2221/68368* (2013.01); *H01L 2221/68381* (2013.01); *H01L 2224/95001* (2013.01); *H01L 2224/951* (2013.01); *H01L 2224/95136* (2013.01); *H01L 2924/1815* (2013.01)

(58) **Field of Classification Search**
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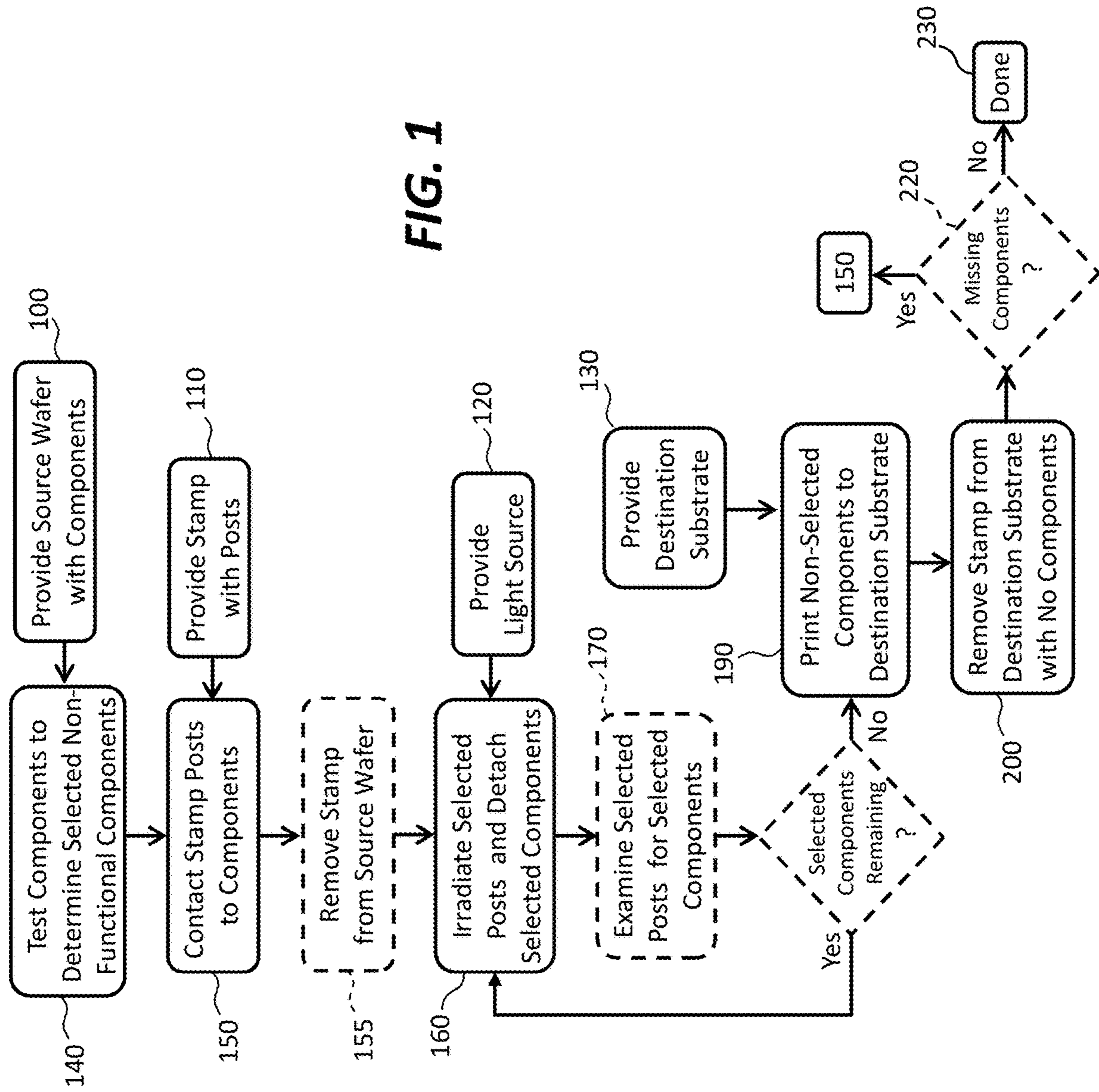


FIG. 1

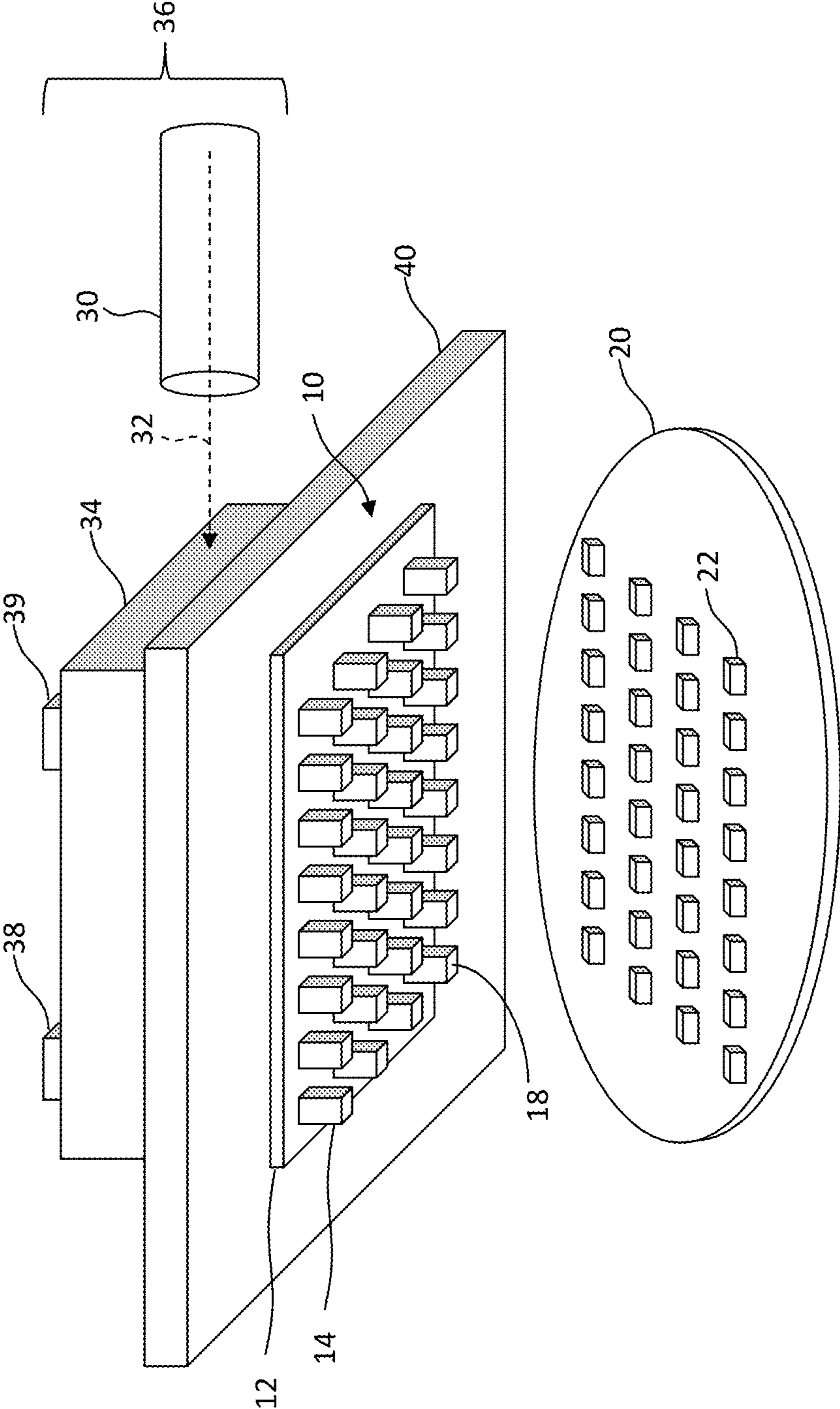


FIG. 2

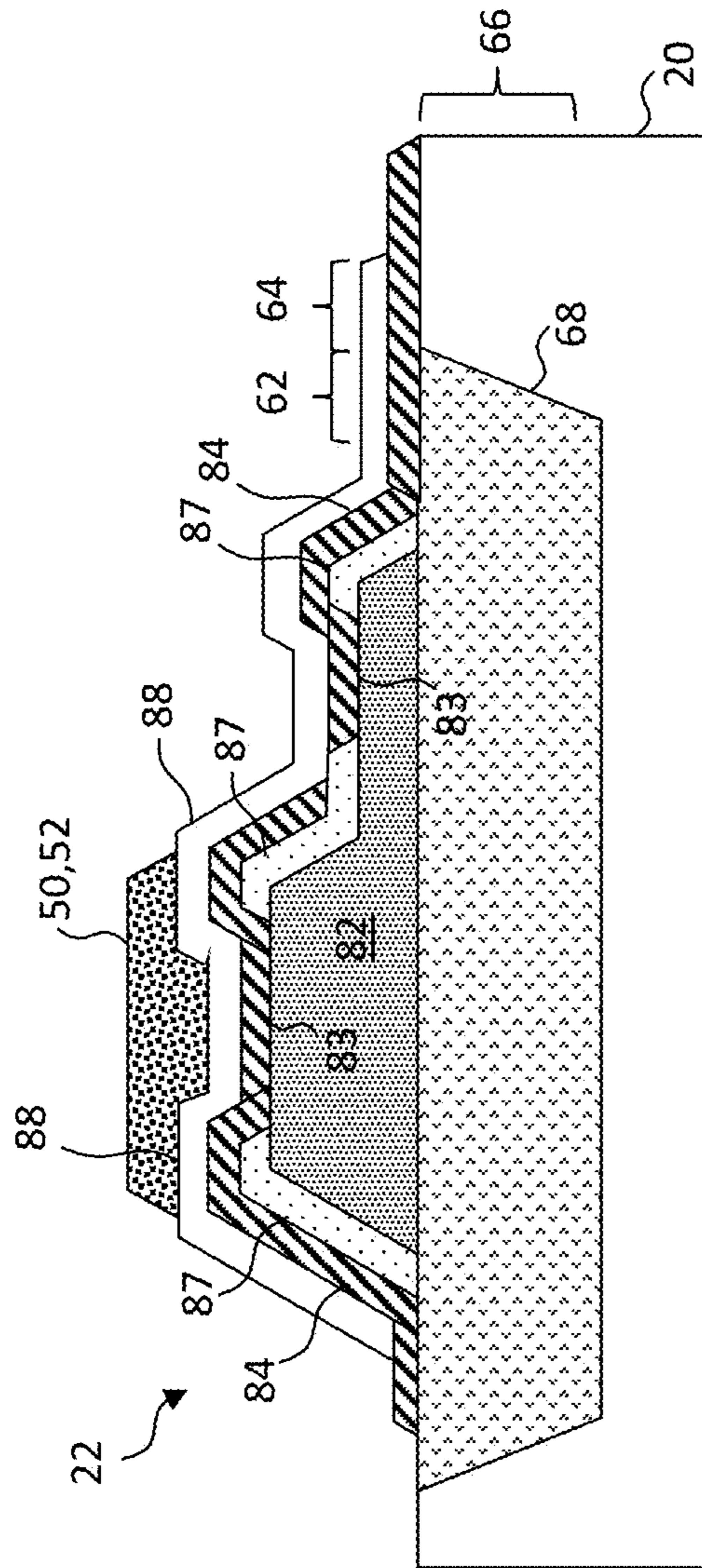


FIG. 3

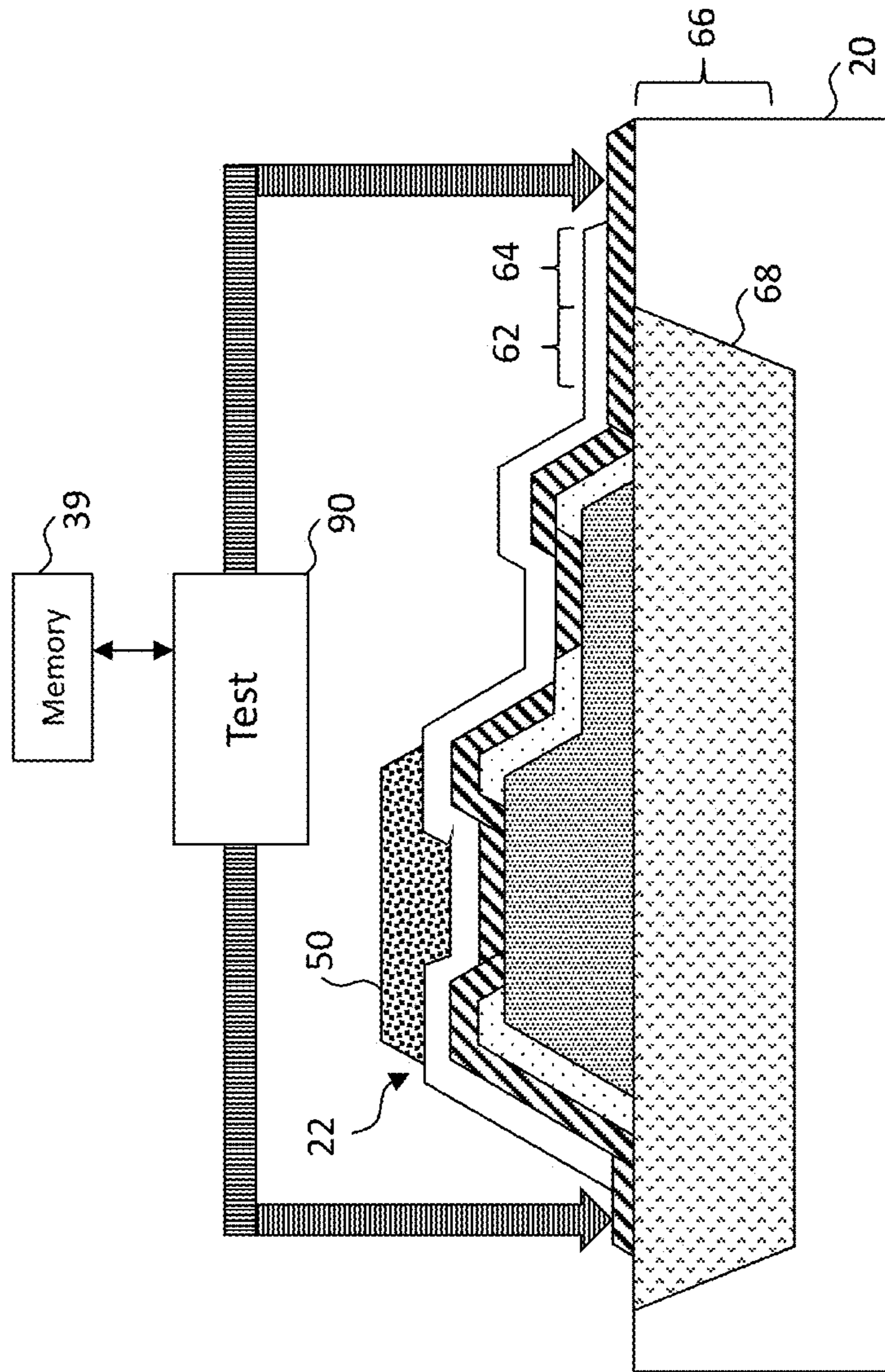


FIG. 4

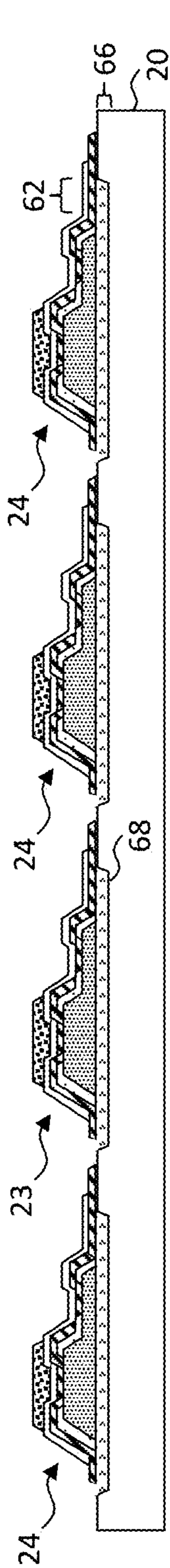


FIG. 5

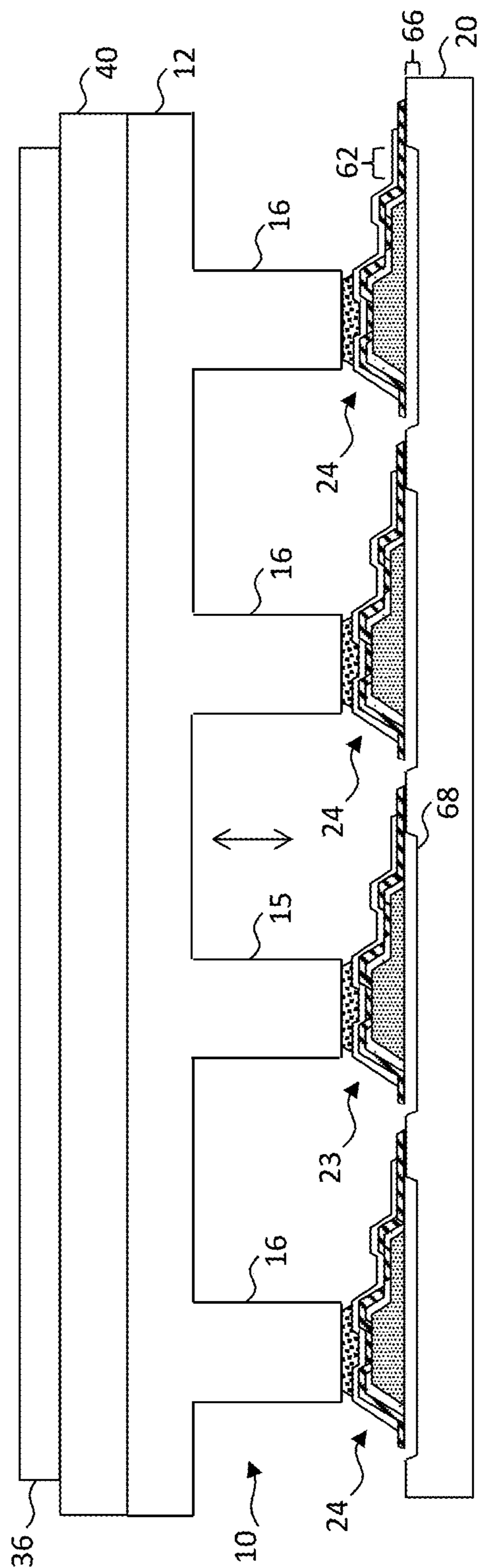


FIG. 6

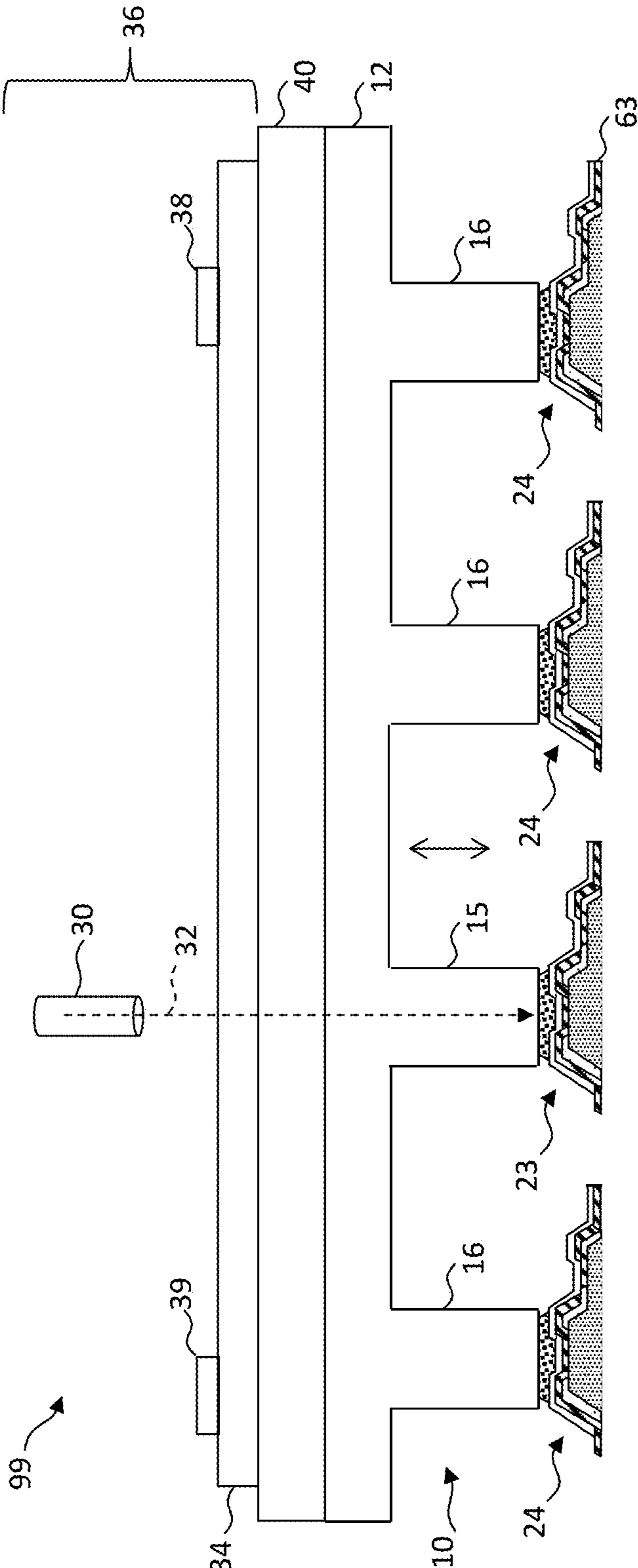


FIG. 7A

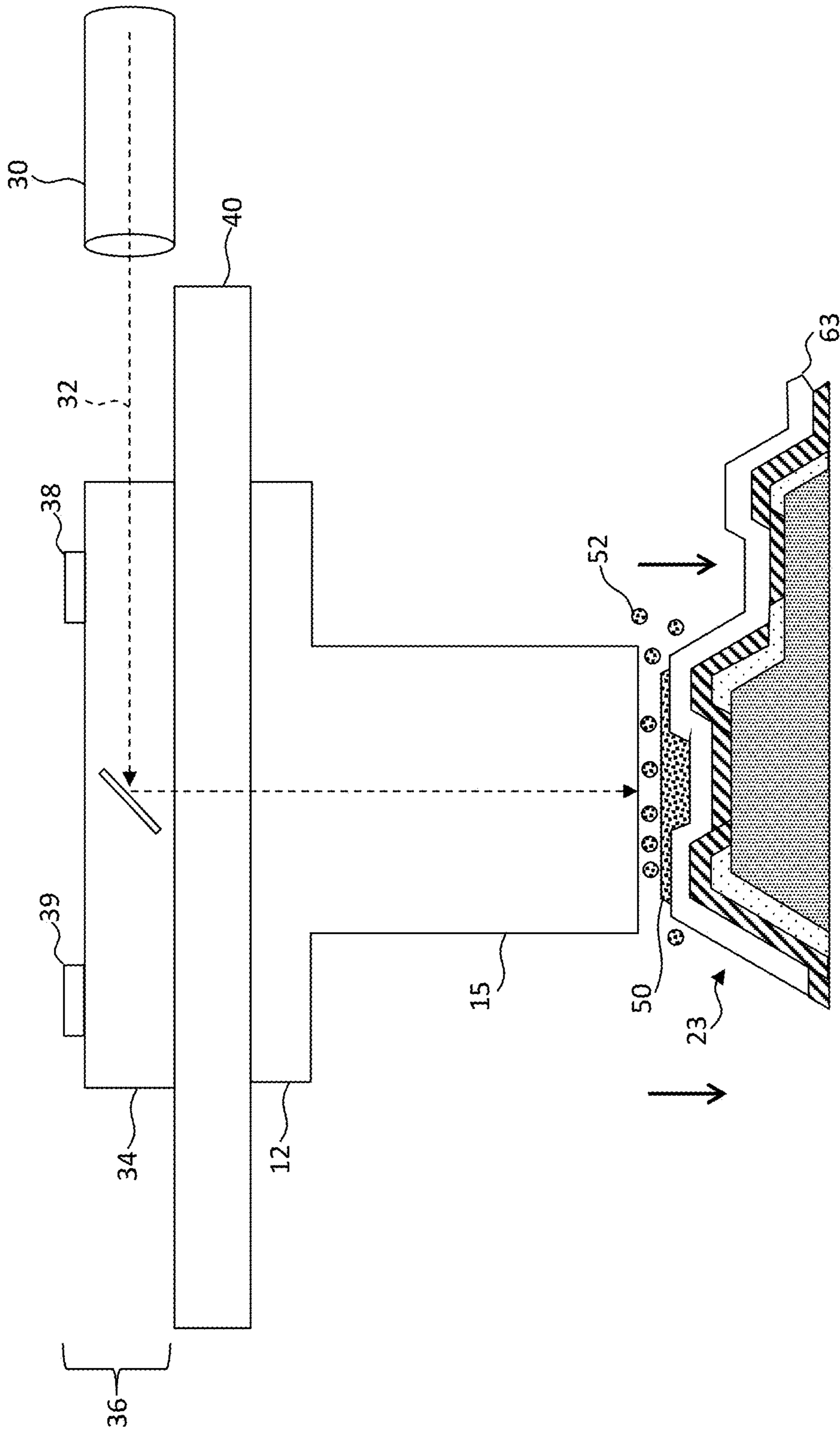


FIG. 7B

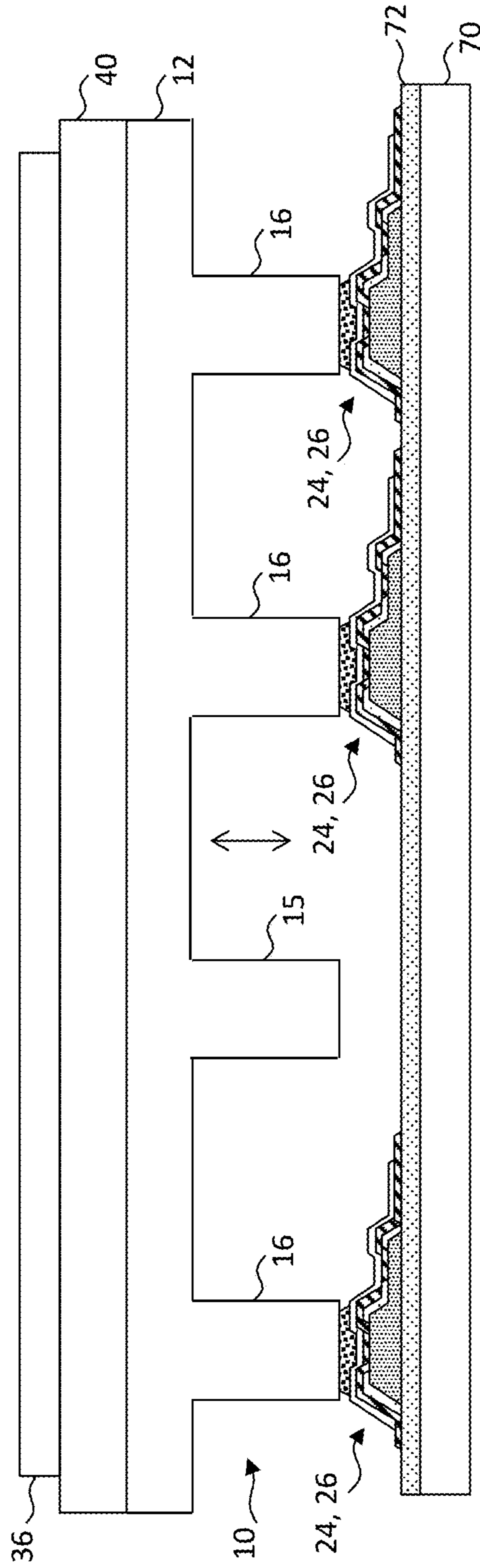


FIG. 8

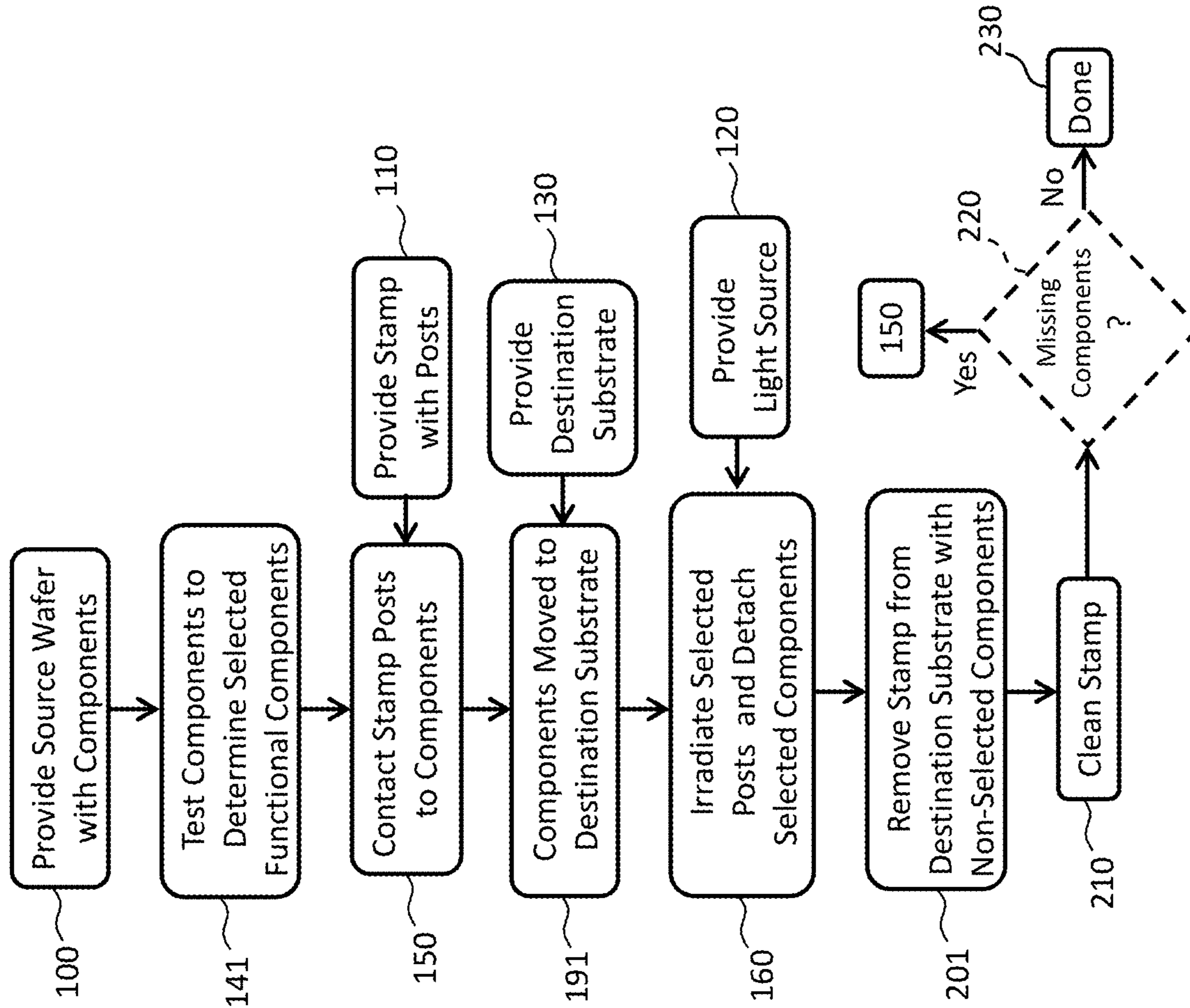


FIG. 9

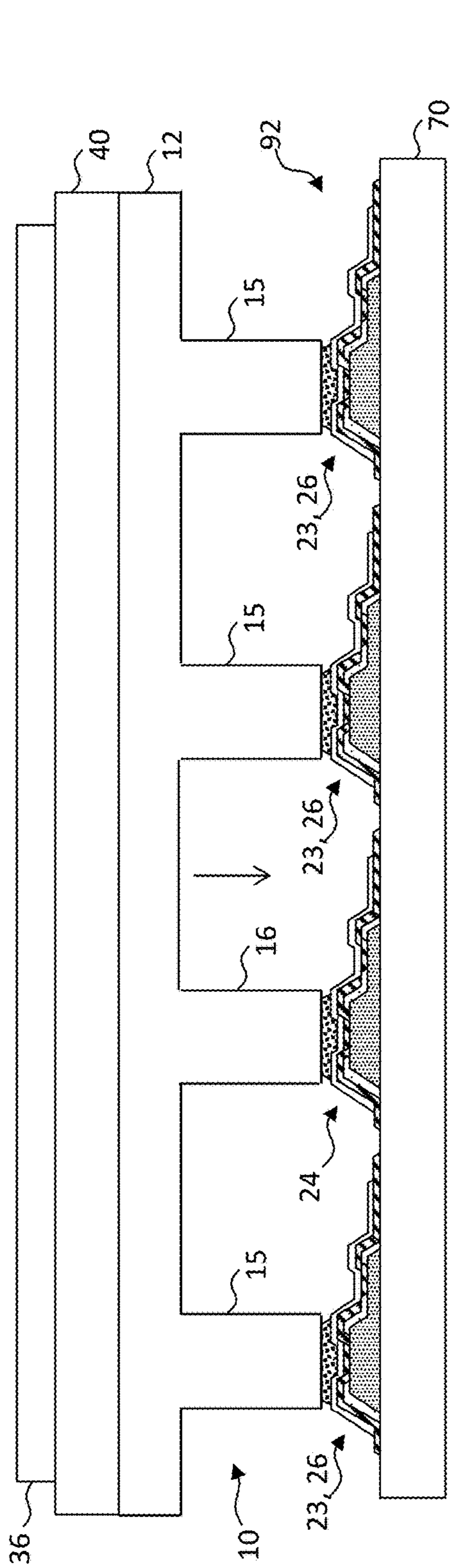


FIG. 10

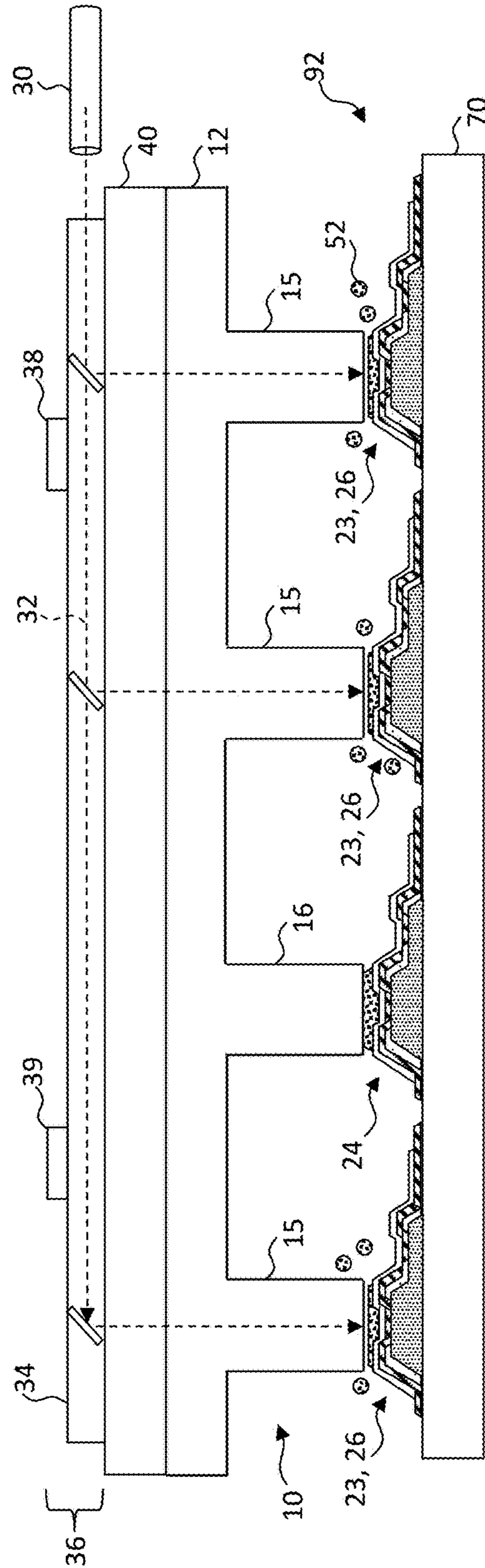


FIG. 11

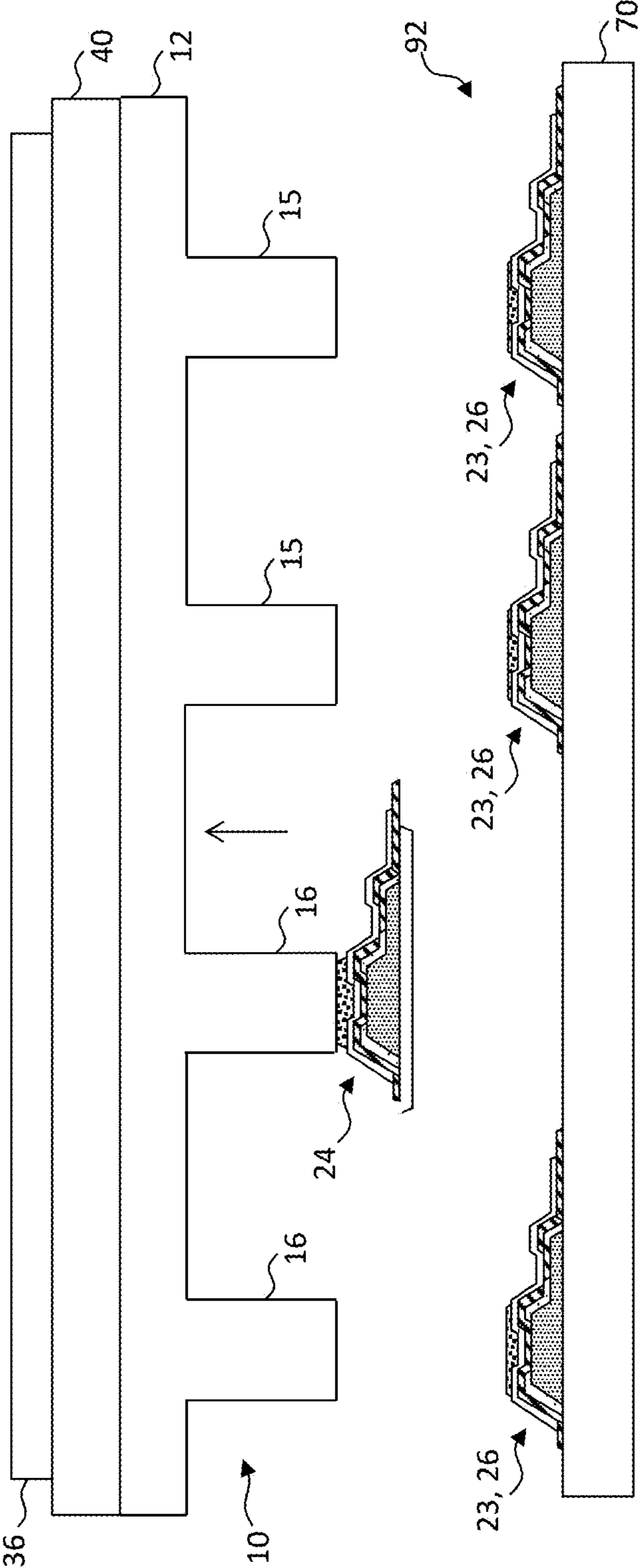


FIG. 12

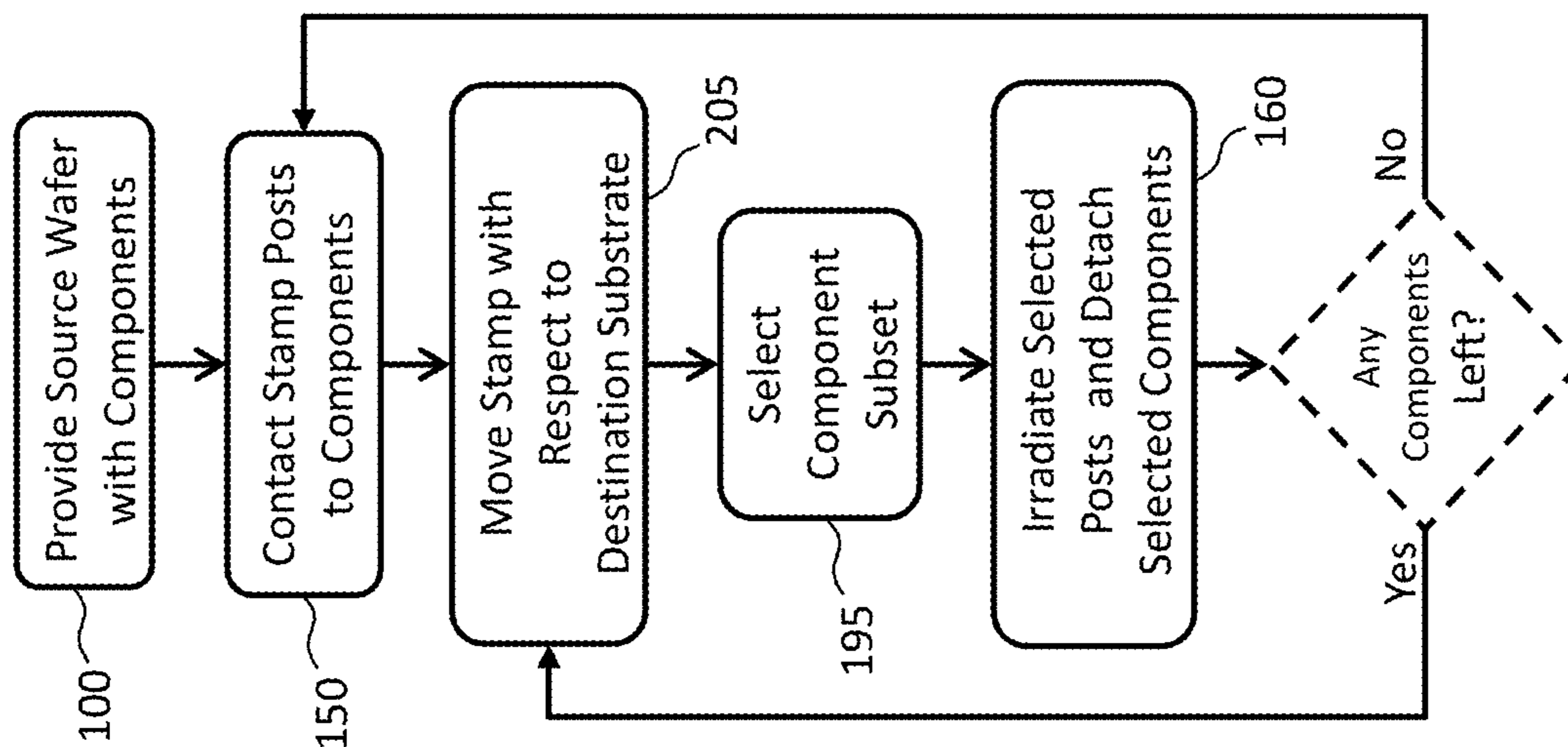


FIG. 13

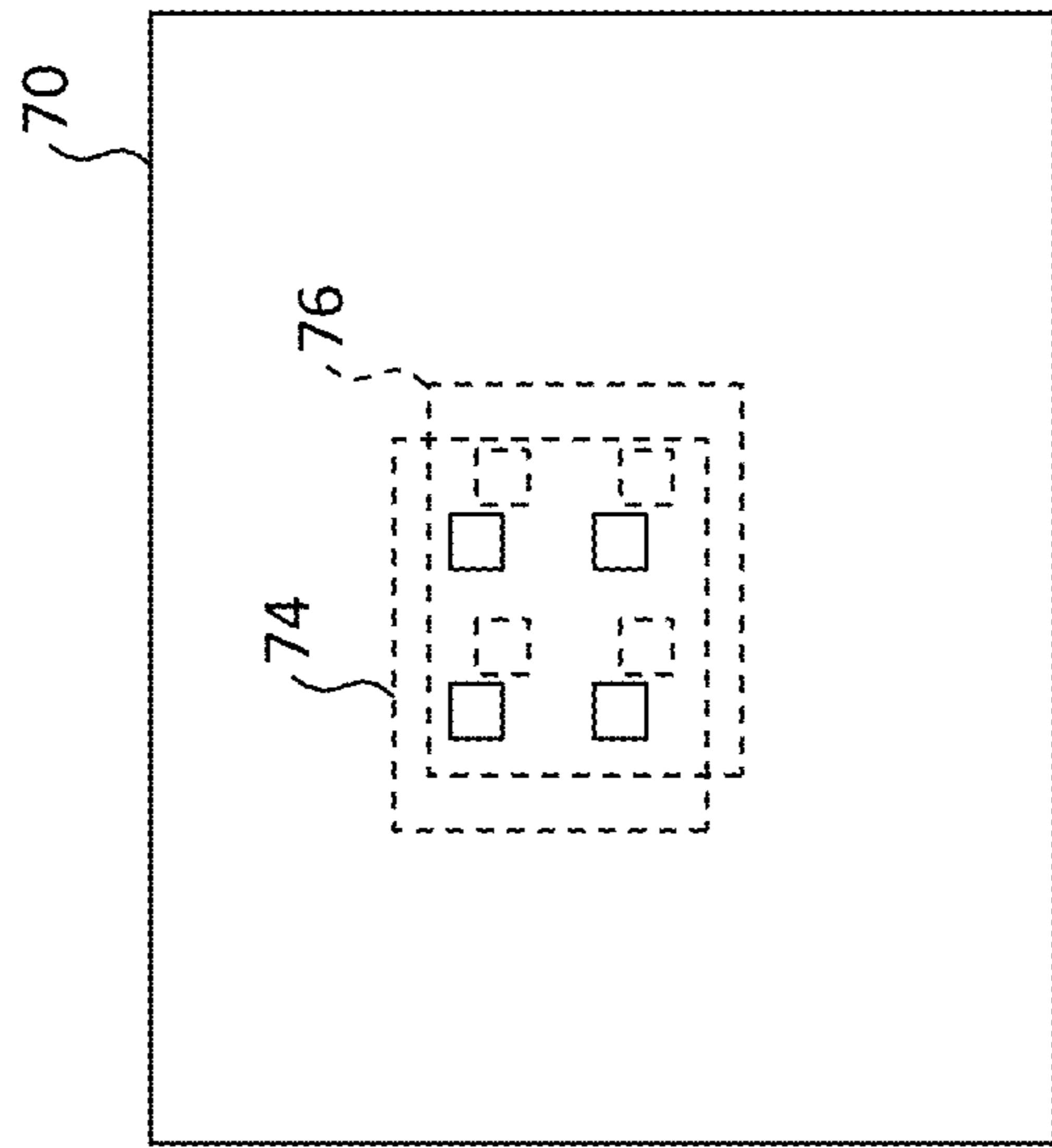


FIG. 14A

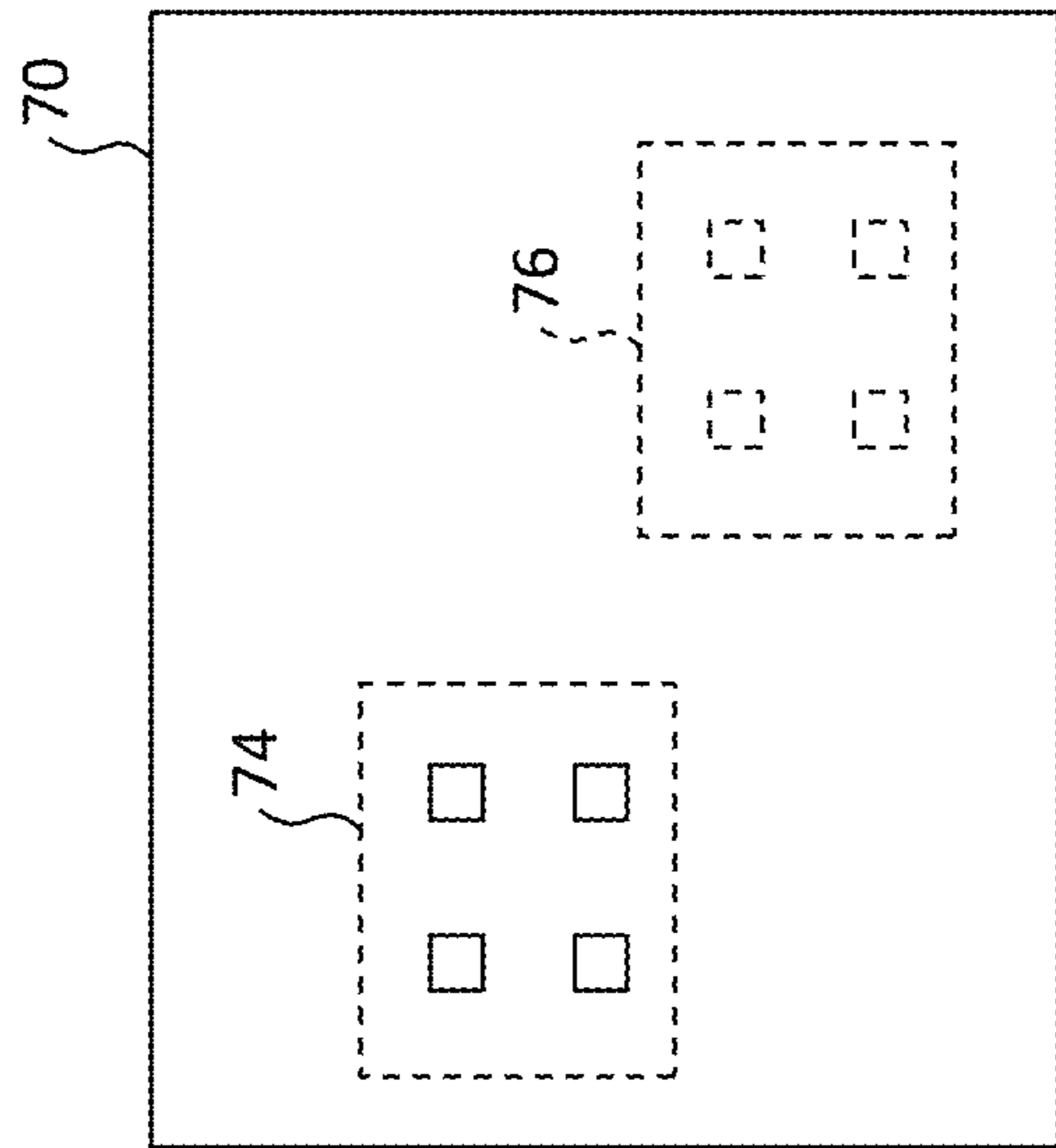


FIG. 14B

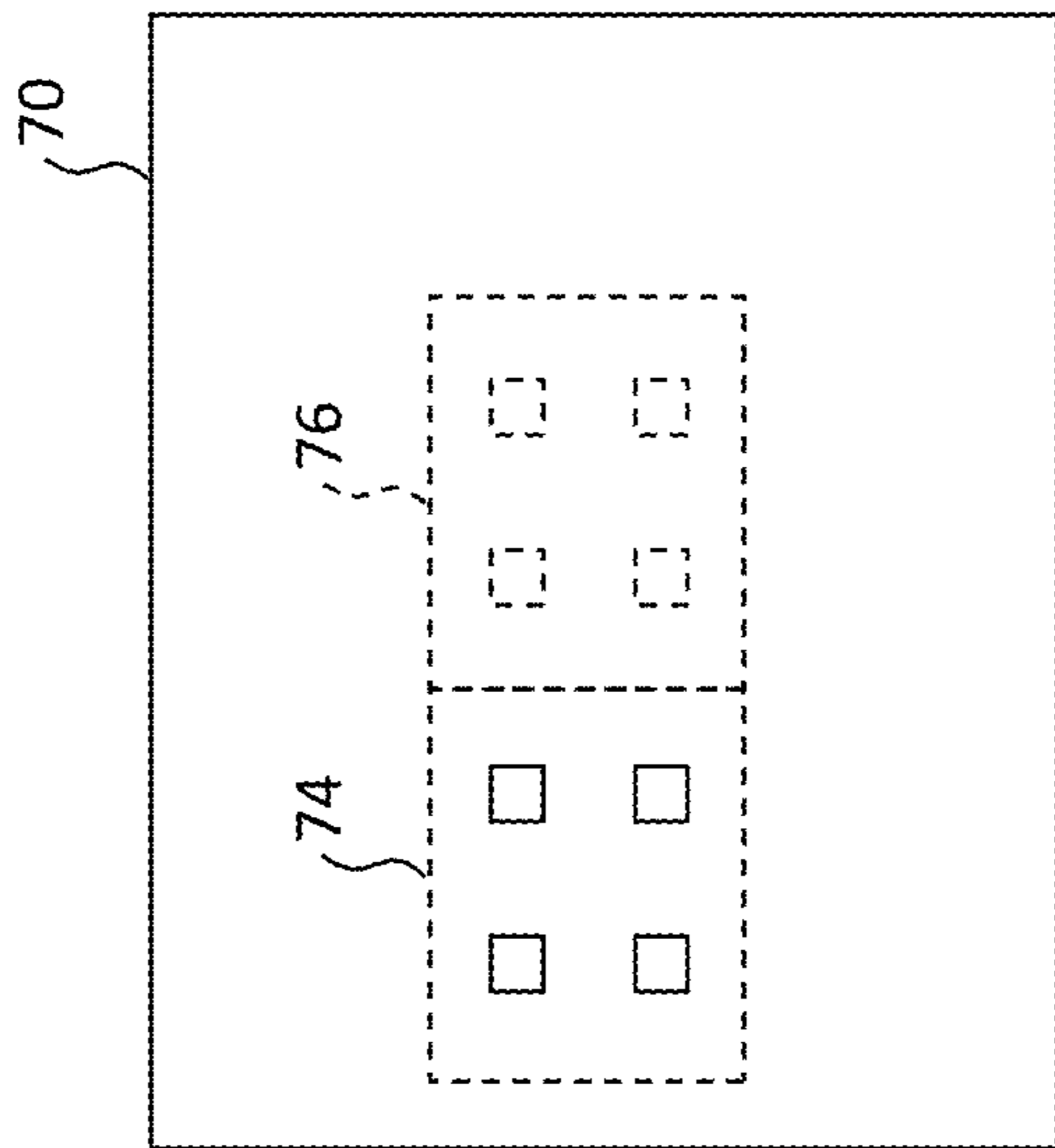


FIG. 14C

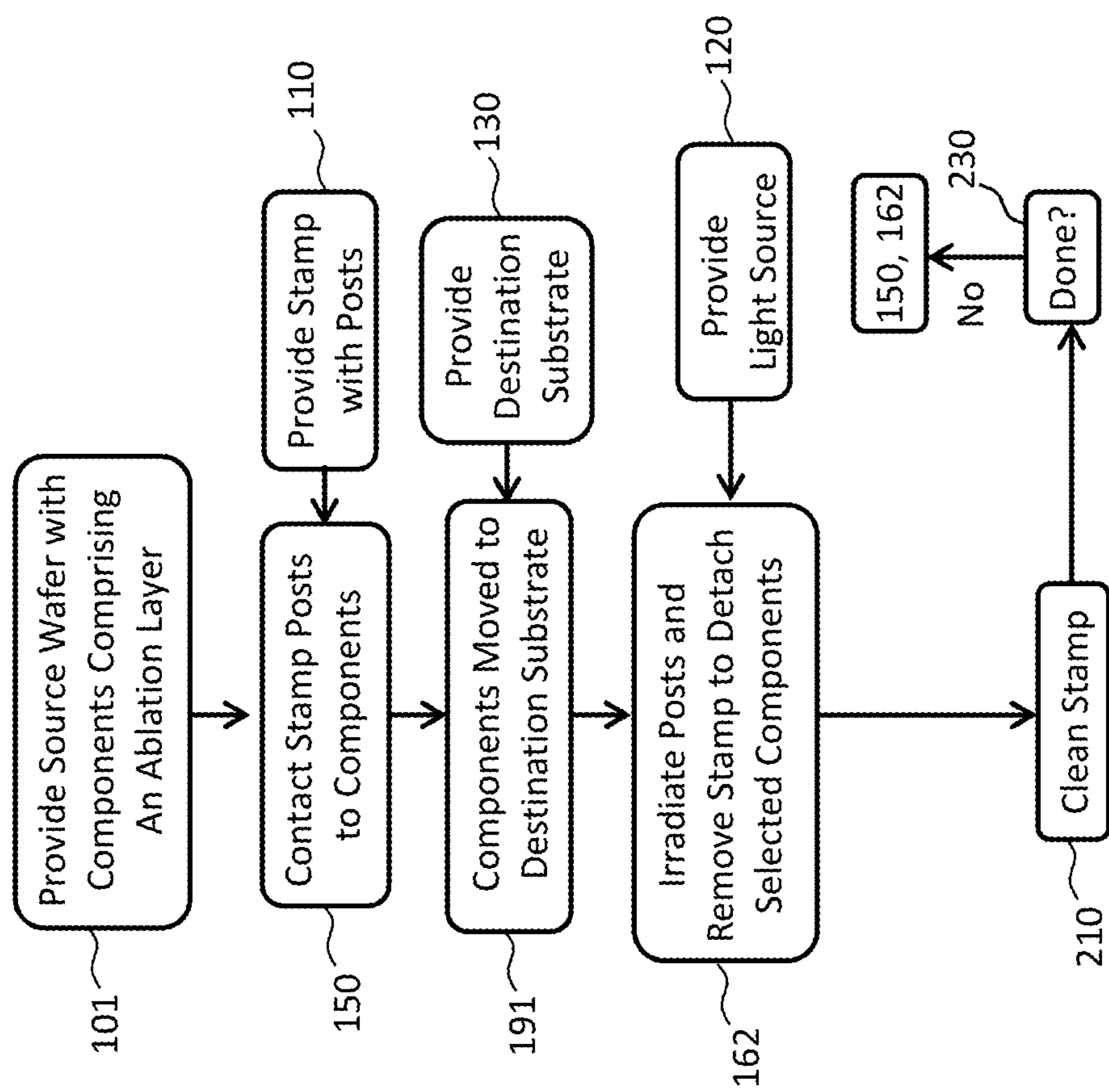


FIG. 15

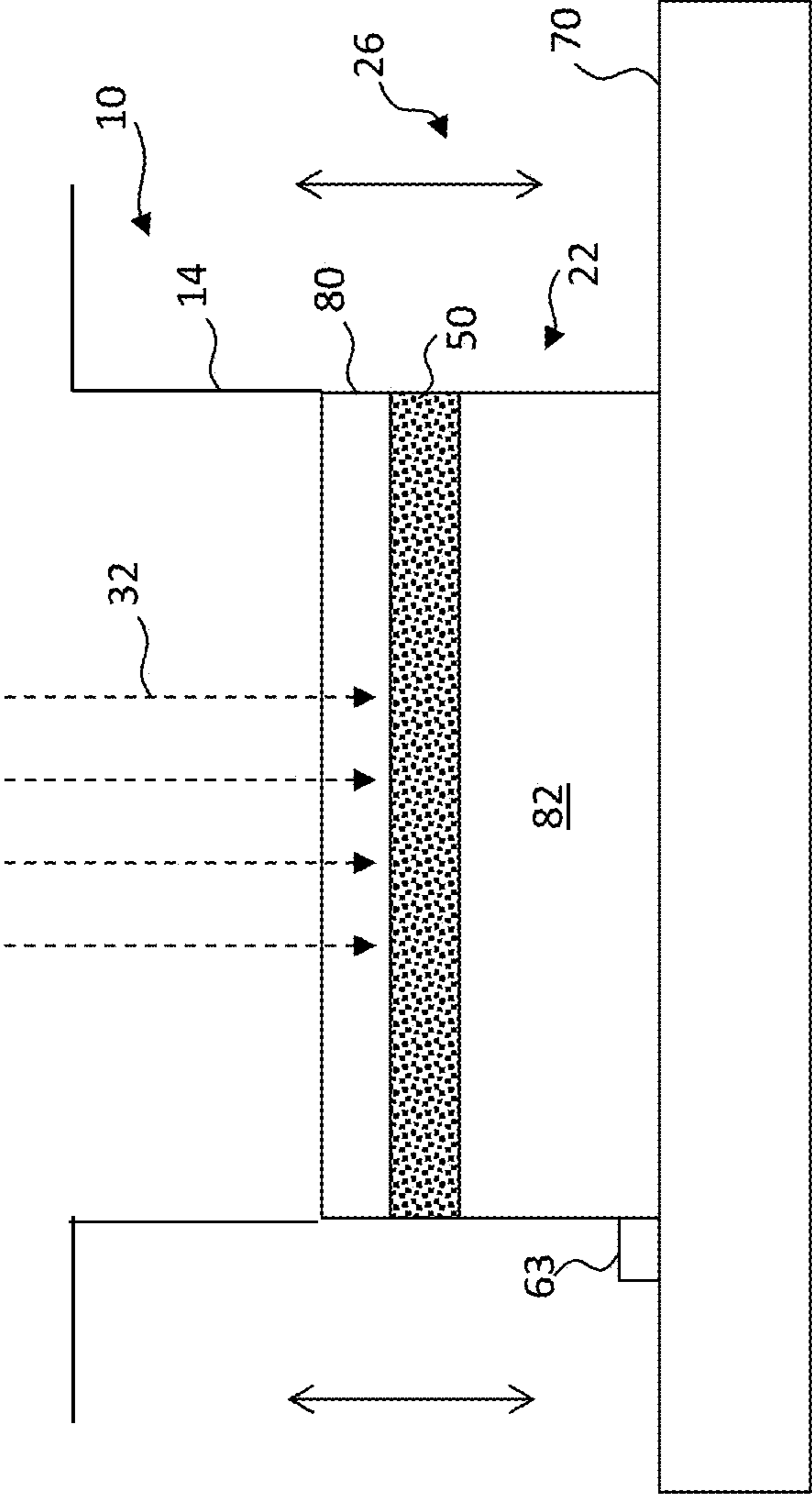


FIG. 16

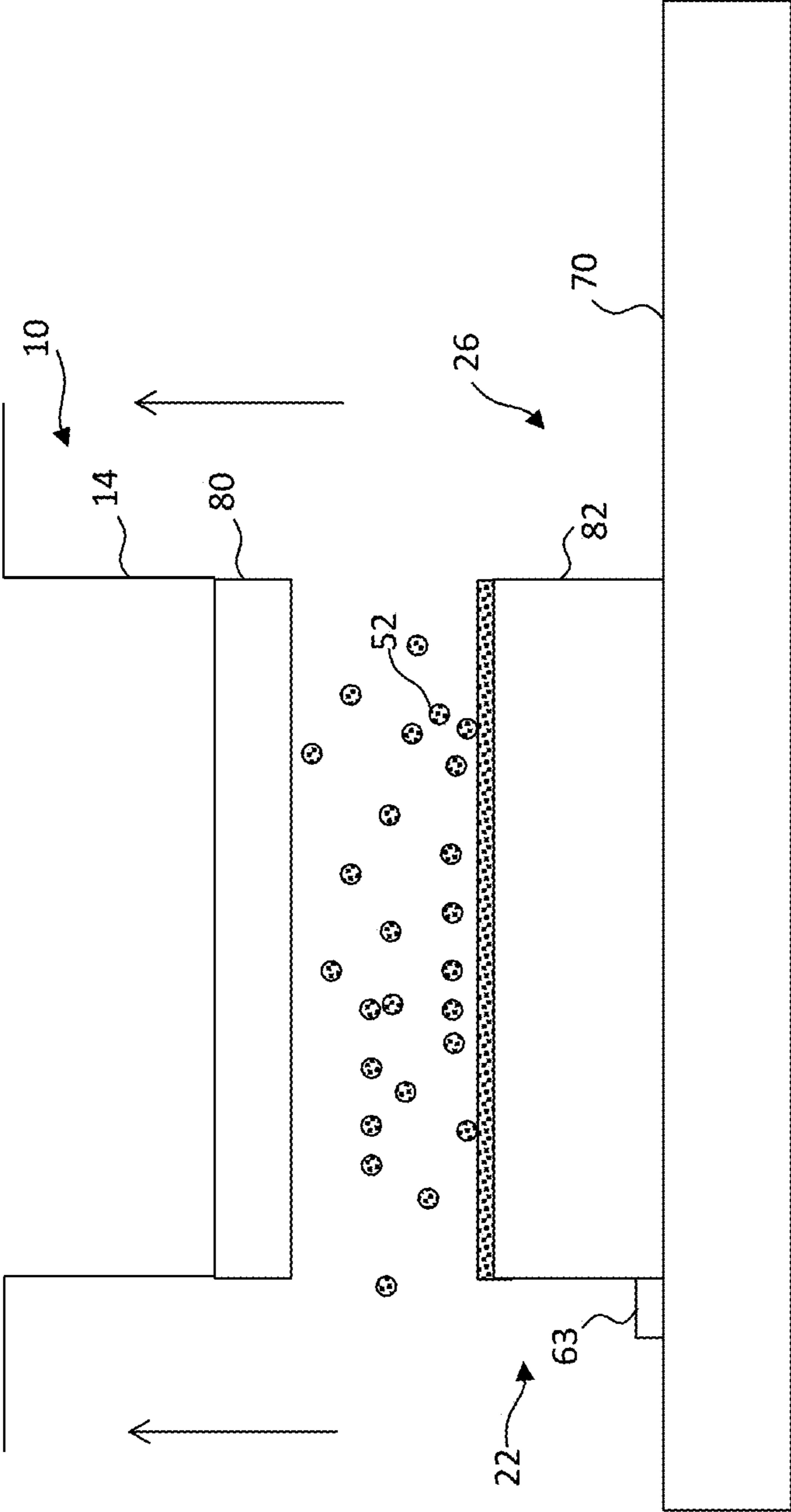


FIG. 17

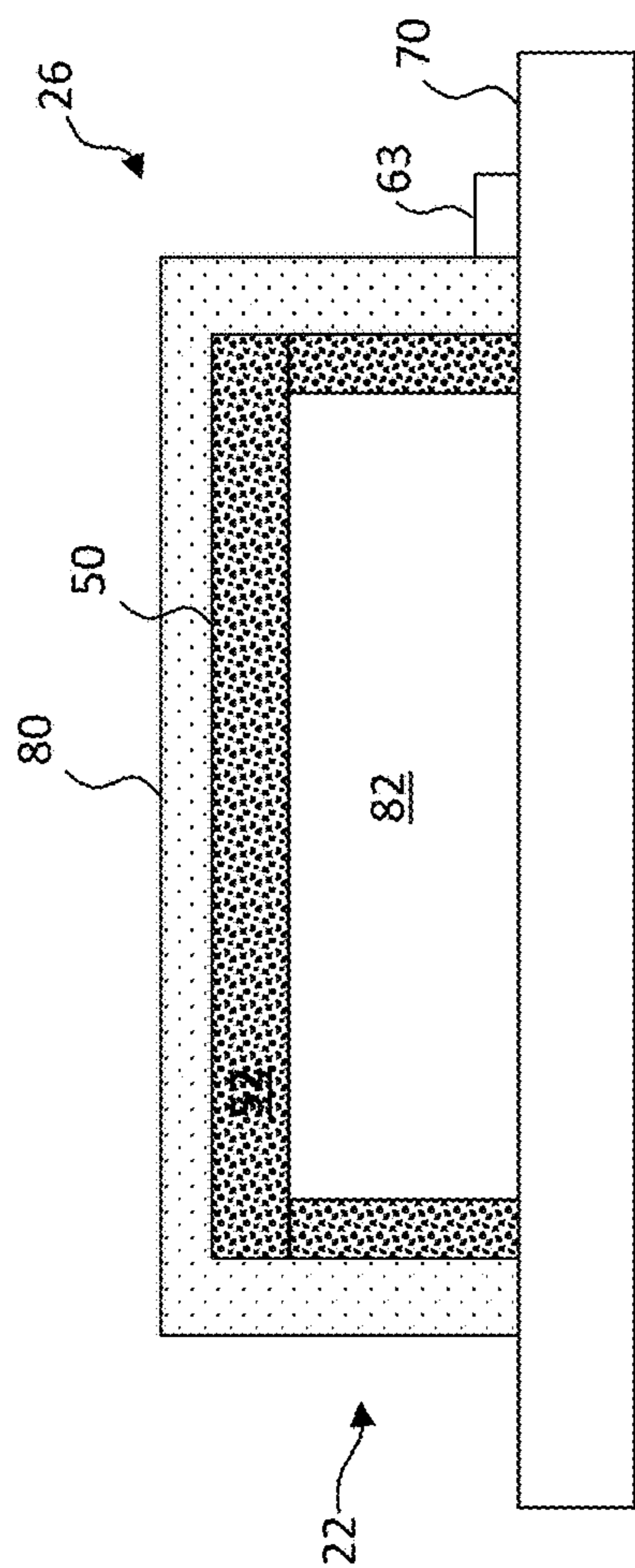


FIG. 18

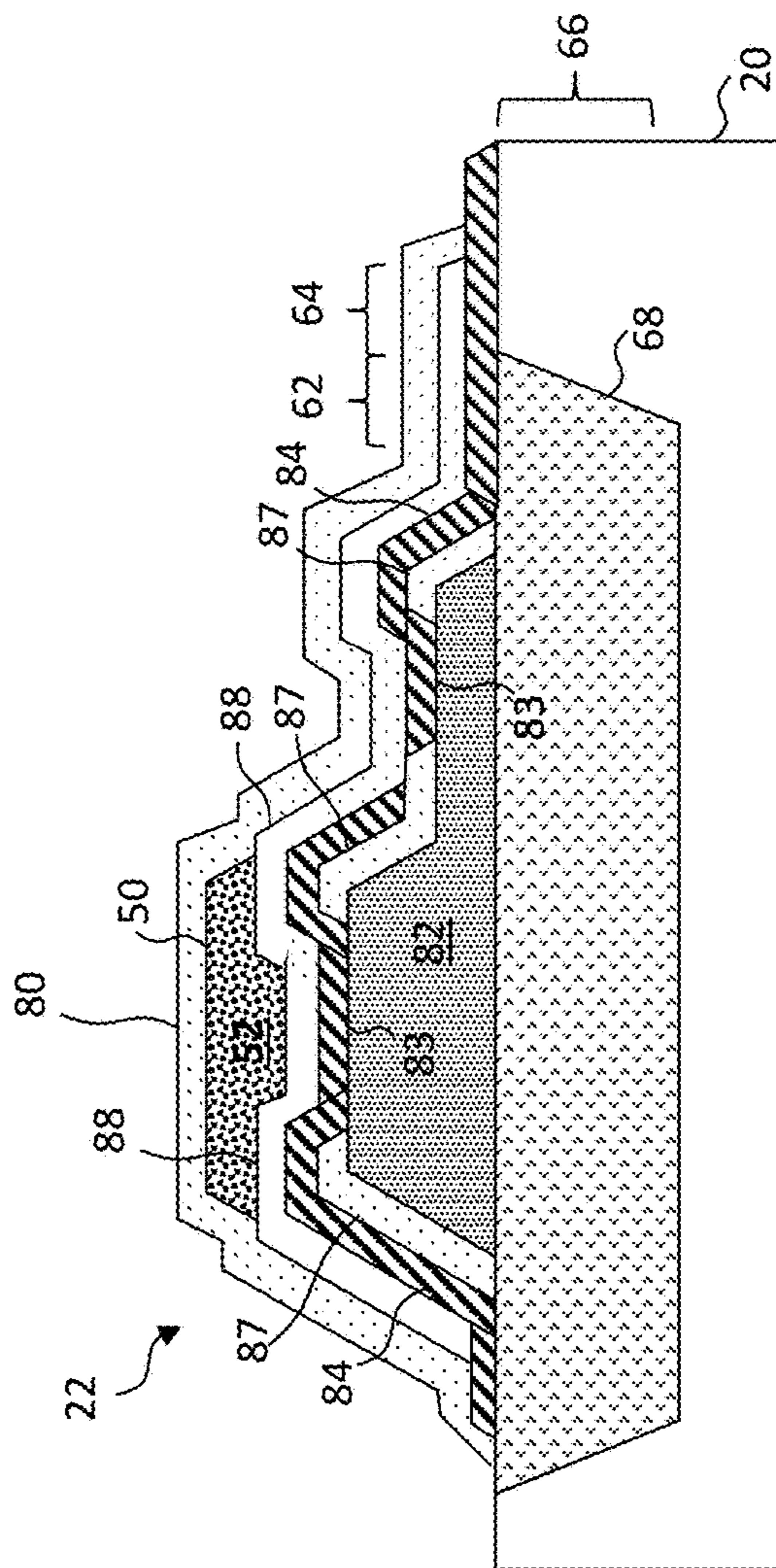


FIG. 19

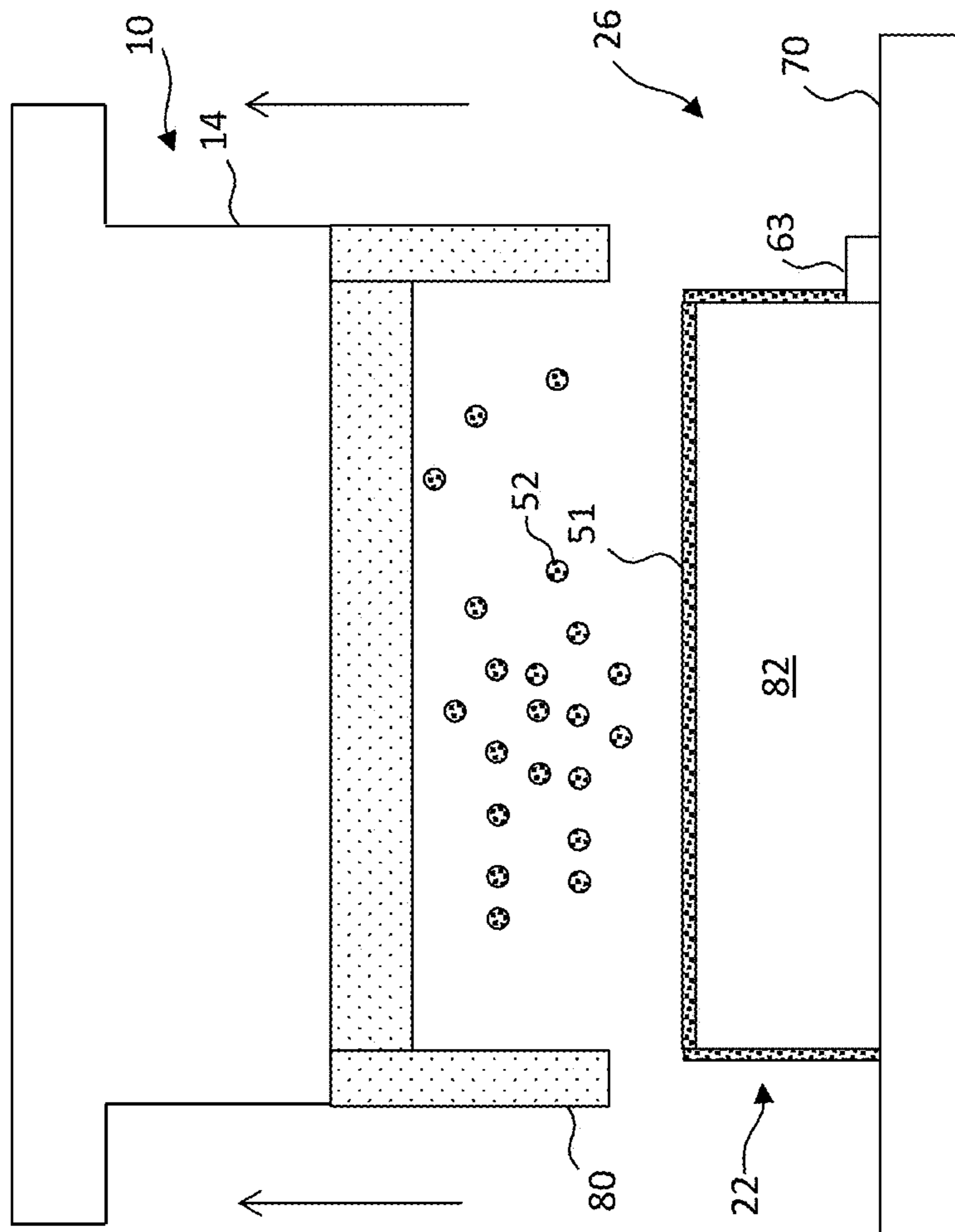


FIG. 20

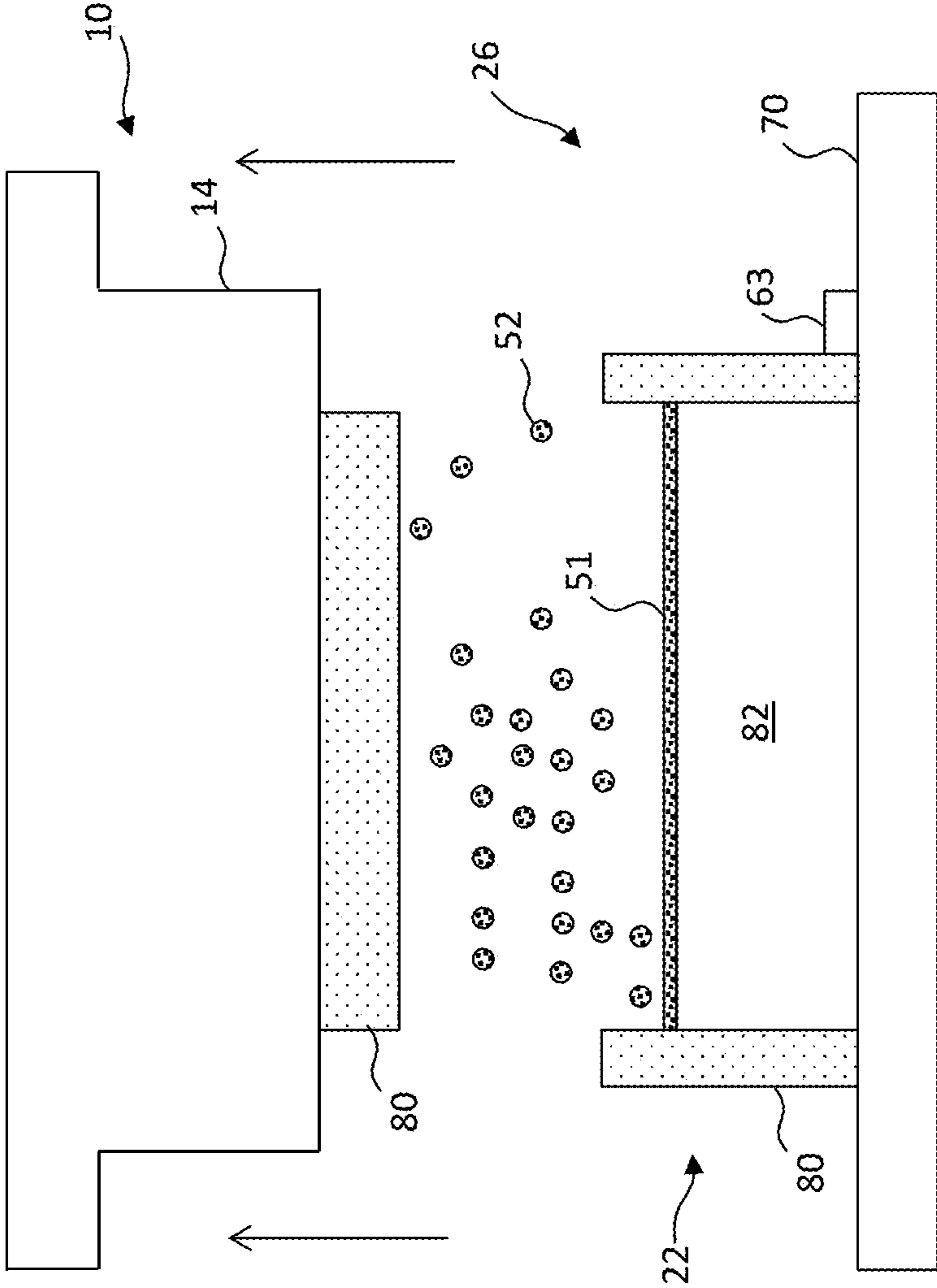


FIG. 21

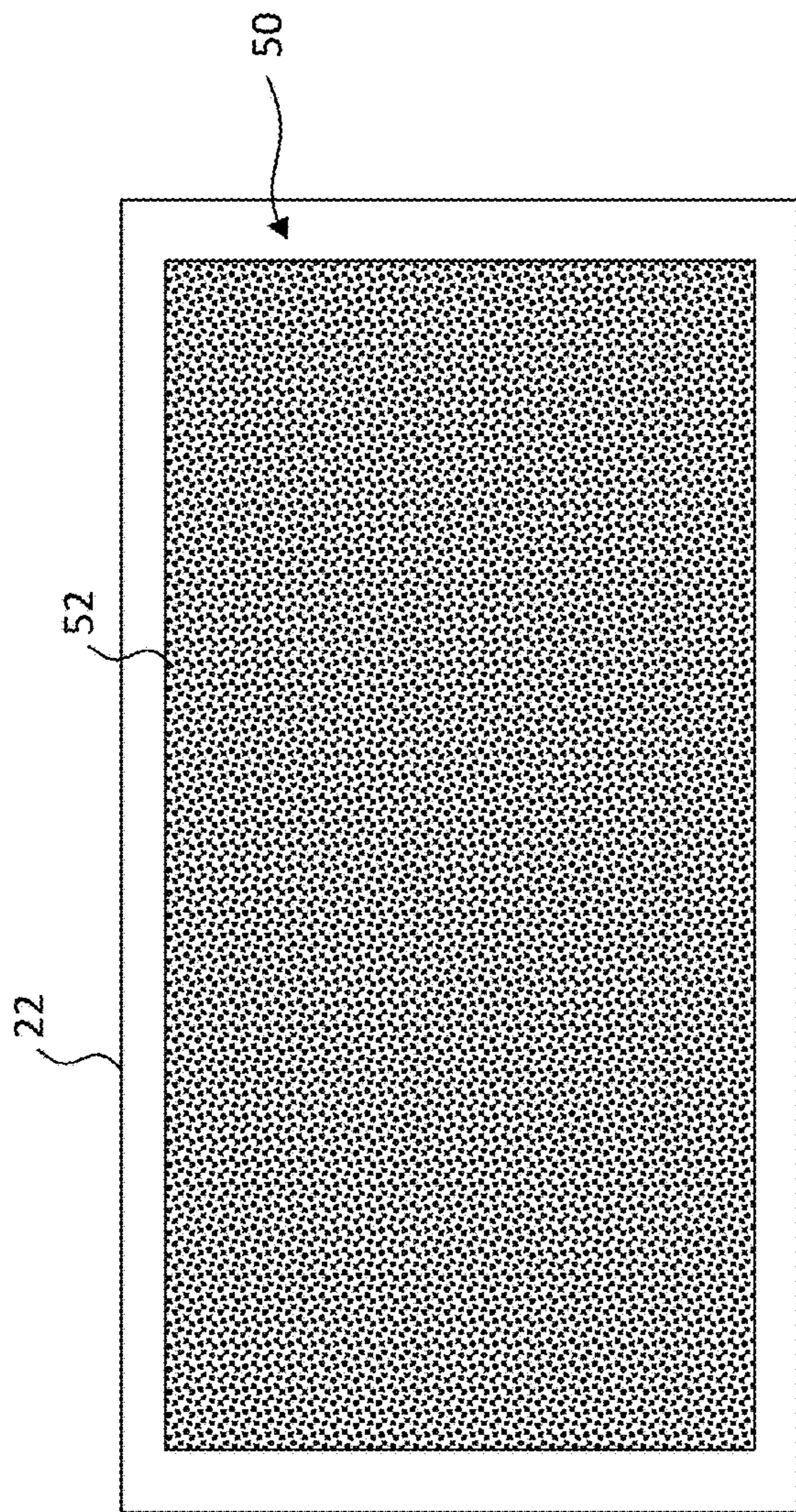


FIG. 22

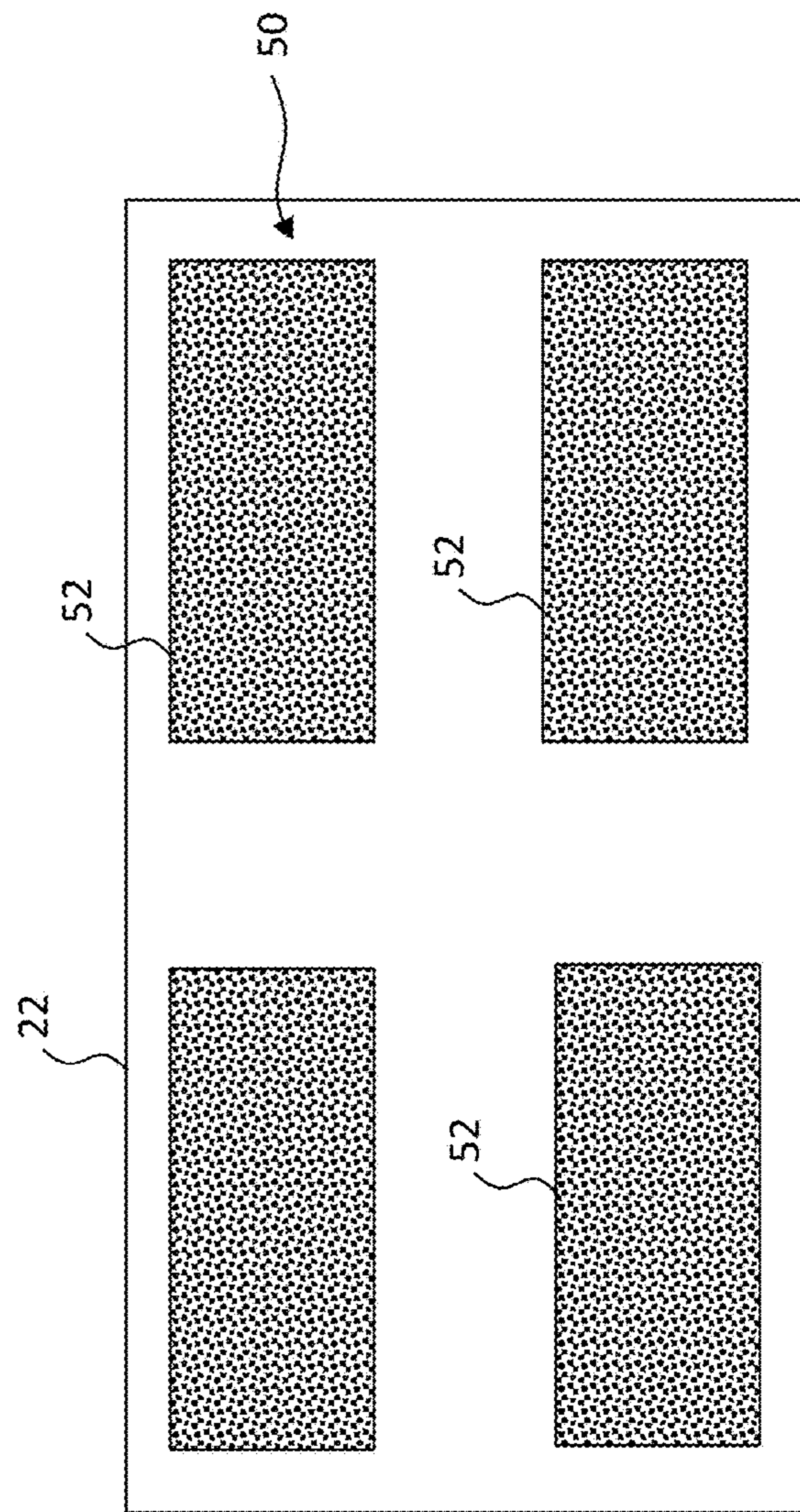


FIG. 23

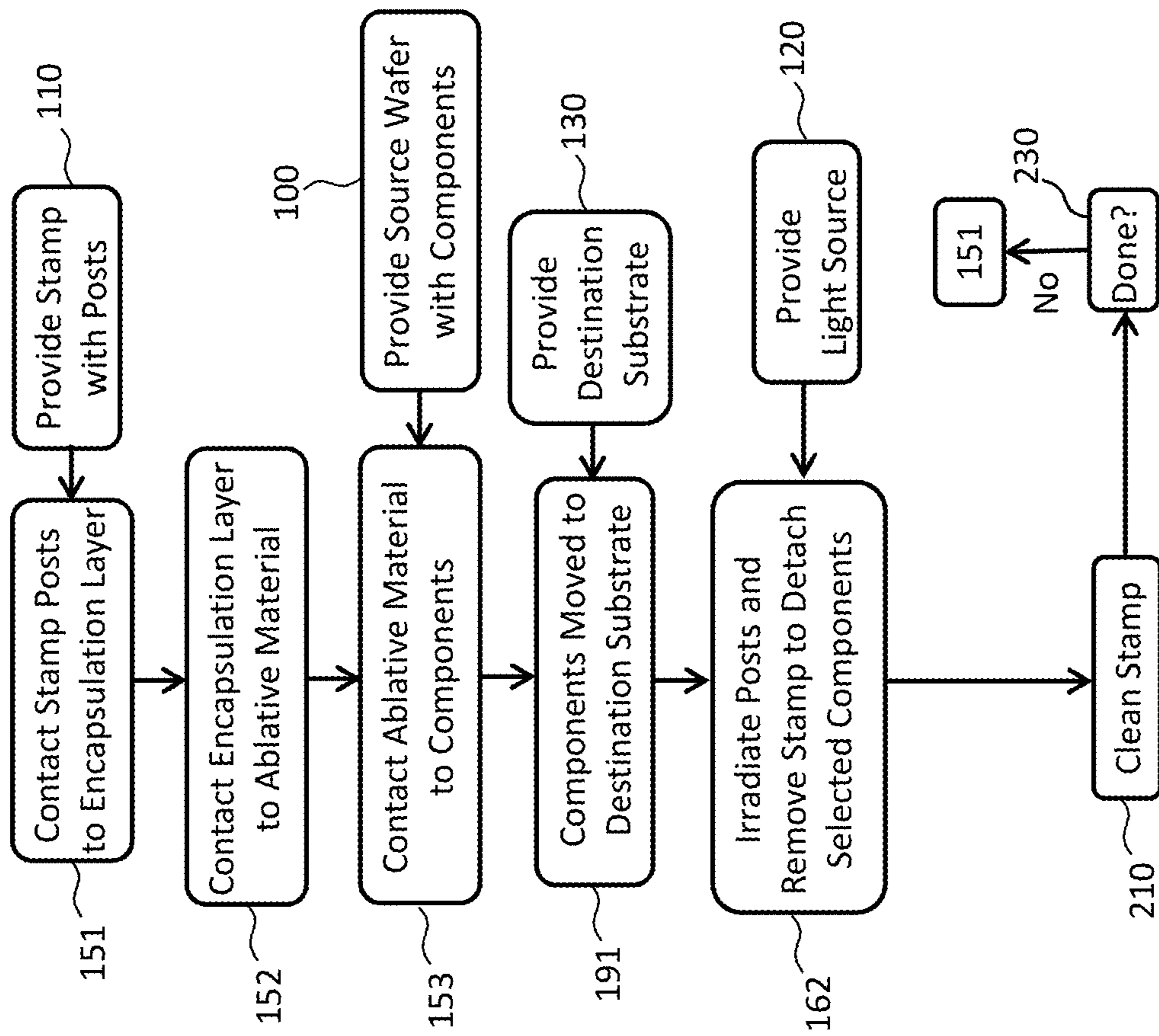


FIG. 24

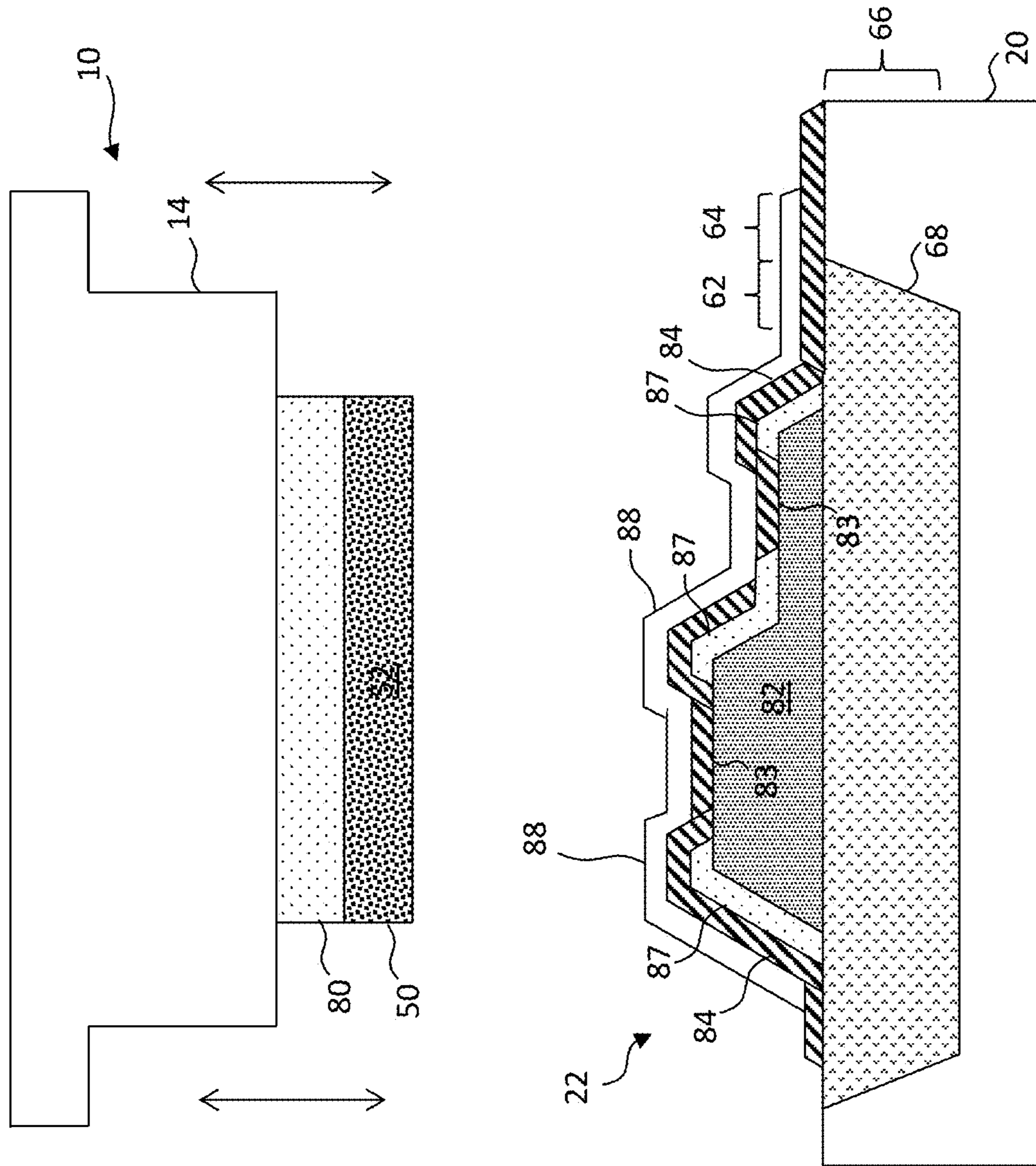


FIG. 25

MICRO-TRANSFER PRINTING WITH SELECTIVE COMPONENT REMOVAL

PRIORITY APPLICATION

This application is a continuation-in-part of U.S. patent application Ser. No. 16/163,559, entitled Transfer Printing with Selective Component Removal, filed Oct. 17, 2018, the disclosure of which is hereby incorporated by reference herein in its entirety.

CROSS REFERENCE TO RELATED APPLICATIONS

This application is related to U.S. Pat. No. 9,358,775, entitled Apparatus and Methods for Micro-Transfer Printing, which is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

The present specification generally relates to systems and methods for micro-transfer printing using a stamp and, in particular, to systems and methods for controllably removing selected components adhered to stamp posts from the stamp.

BACKGROUND

Conventional methods such as pick-and-place for applying integrated circuits to a destination substrate are limited to relatively large devices, for example having a dimension of a millimeter or more and it is often difficult to pick up and place ultra-thin, fragile, or small devices using such conventional technologies. More recently, micro-transfer printing methods have been developed that permit the selection and application of such ultra-thin, fragile, or small devices without causing damage to the devices themselves.

Micro-transfer printing enables deterministically removing arrays of micro-scale, high-performance devices from a native source wafer, typically a semiconductor wafer on which the devices are constructed, and assembling and integrating the devices onto non-native destination substrates, such as glass or polymer substrates. In a simple embodiment, micro-transfer printing is analogous to using a rubber stamp to transfer liquid-based inks from an ink-pad onto paper. However, the “inks” are typically composed of high-performance solid-state semiconductor devices and the “paper” can be substrates, including glass, plastics, ceramics, metals, or other semiconductors, for example. An example micro-transfer printing process leverages engineered elastomer stamps coupled with high-precision motion-controlled print-heads to selectively pick up and print large arrays of micro-scale devices from a source native wafer onto non-native destination substrates.

Adhesion between an elastomer transfer device and a printable element can be selectively tuned by varying the speed of the print-head, for example. This rate-dependent adhesion is a consequence of the viscoelastic nature of the elastomer used to construct the transfer device. When the transfer device is moved quickly away from a bonded interface, the adhesion is large enough to “pick” the printable elements away from their native substrates, and conversely, when the transfer device is moved slowly away from a bonded interface the adhesion is low enough to “let go” or “print” the element onto a foreign surface. This process may be performed as a massively parallel operation

in which the stamps can transfer, for example, hundreds to thousands of discrete structures in a single pick-up and print operation.

Micro-structured stamps may be used to pick up micro devices from a source substrate, transport the micro devices to the destination, and print the micro devices onto a destination substrate. A transfer device (e.g., micro-structured stamp) can be created using various materials. Posts on the transfer device can be designed to pick up material from a pick-able object and then print the material to the target substrate. The posts can be formed in an array. For effective, high-yield printing, when picking up the material it is important that the posts are in close contact with the material (e.g., micro integrated circuits) being transferred or printed.

In any printing operation, it is important that the destination (receiving) substrate include functional devices at every desired location on the destination substrate at the end of an assembly process and it is therefore important to provide methods and systems for ensuring completely functional micro-transfer-printed structures.

SUMMARY

The present disclosure provides, inter alia, systems and methods for transferring micro-devices from a native micro-device source wafer or micro-device source substrate to a non-native destination substrate. According to some embodiments of the present disclosure, a method of micro-transfer printing comprises providing a component source wafer or micro-device source substrate having micro-transfer printable components disposed on or in the component source wafer or micro-device source substrate. Micro-transfer printable components and micro-transfer printed components can be referred to as components herein. Selected ones of the micro-transfer printable components are selected components and the micro-transfer printable components that are not selected are non-selected components.

In some embodiments, a stamp comprising a body and spaced-apart posts protruding away from the body to a distal end of the posts is provided. The posts have a spatial distribution on the body matched to a spatial distribution of the micro-transfer printable components on or in the component source wafer. The stamp can be a visco-elastic stamp, for example comprising PDMS (polydimethylsiloxane). A provided light source can controllably irradiate each of the posts with light through the body.

Each of the posts is contacted to a component of the micro-transfer printable components to adhere the component to a distal end of the post, for example with van der Waals forces. Posts contacting the selected components are selected posts and posts contacting the non-selected components are non-selected posts. Controllably irradiating with a light source means that each of the posts can be irradiated, or not, by the light source depending on whether the post is a selected post or a non-selected post. Selected posts can be irradiated and non-selected posts can be non-irradiated.

The stamp with the adhered components is removed from the component source wafer and each of the selected posts are irradiated through the body with the light to detach the selected components adhered to the selected posts from the selected posts, leaving the non-selected components adhered to the non-selected posts. The body and the posts are substantially transparent to the light.

Some embodiments of the present disclosure comprise providing a destination substrate and contacting the non-selected components to the destination substrate using the stamp to adhere the non-selected components to the desti-

nation substrate, or to a layer on the destination substrate, after detaching the selected components from the selected posts. The step of providing a destination substrate can comprise providing an adhesive layer on the destination substrate and the step of contacting the non-selected components to the destination substrate can comprise directly contacting the non-selected components to the adhesive layer.

In some embodiments of the present disclosure, the component source wafer comprises a patterned sacrificial layer defining spaced-apart sacrificial portions and anchors, and the components are each disposed over a sacrificial portion and physically connected to an anchor by a tether (e.g., at least one anchor by at least one tether). The steps of contacting the posts to the components and removing the stamp can fracture or break the tethers or separate the tethers from the components.

Irradiation of selected posts can irradiate a distal end of the selected posts, can irradiate selected components adhered to the distal ends of the selected posts, can irradiate a portion of the selected components adhered to the distal ends of the selected posts, can irradiate a layer of the selected components adhered to the distal ends of the selected posts, or any combination of these. In some embodiments of the present disclosure, each of the components comprises an ablation layer and the irradiation of the selected posts vaporizes at least a portion of the ablation layer of the selected components, for example a portion in contact with the distal end of the selected post.

In some embodiments, the posts and the components (e.g., a portion thereof) have different coefficients of thermal expansion (CTEs). In some embodiments, irradiation of the selected posts can heat the selected posts or the distal ends of the selected posts so that the distal end of the selected posts expands differently from the selected components adhered to the selected posts so that a thermal shear (a shear force due to temperature differences) takes place between the selected components and the distal ends of the selected posts, detaching the selected components adhered to the distal ends of the selected posts from the distal ends of the selected posts. In some embodiments, irradiation of the selected components heats the selected components, a portion of the selected components, or a layer or portion of a layer of the selected components so that the distal end of the selected posts to which the selected components are adhered expands differently from the selected components adhered to the selected posts so that a thermal shear takes place between the selected components and the distal ends of the selected posts, detaching (e.g., assisting in detaching along with stamp 10 motion) the selected components adhered to the distal ends of the selected posts from the distal ends of the selected posts.

In some embodiments of the present disclosure, each of the components is tested before contacting the posts to the components to determine faulty components. Faulty components are selected so that each of the selected components is a faulty component. In some embodiments of the present disclosure, components are selected that are not faulty so that each selected component is a non-faulty component. In some embodiments, selected components have at least one characteristic different from a characteristic of non-selected components (e.g., independent of whether any selected or non-selected component is faulty or not). In some embodiments, a mapping of the selected components and the non-selected components is provided.

In some embodiments of the present disclosure, a disposal area is provided and the stamp is moved to the disposal area

before the selected posts are irradiated so that irradiating the selected posts detaches the selected components from the selected posts and disposes the selected components in the disposal area.

Some embodiments of the present disclosure comprise providing a destination substrate and moving the stamp to the destination substrate before irradiating the selected posts so that irradiating the selected posts detaches the selected components from the selected posts and adheres the selected components to the destination substrate or to a layer on the destination substrate. Non-selected components are not adhered to the destination substrate. In some embodiments, the selected components are in contact with the destination substrate during the irradiation. In some embodiments, the selected components in contact with the destination substrate and the selected posts are removed from the selected components during the irradiation, so that the steps of irradiation and removal of the stamp from the selected components occurs at the same time, occur partially at the same time, or overlap in time. By removing the selected posts from the selected components during the irradiation step (e.g., by removing the stamp), the selected components are prevented from re-adhering to the selected posts after the irradiation is complete. In some embodiments, the selected components are adjacent to but not in contact with the destination substrate so that the selected components are detached from the selected posts and the selected components travel from the selected posts to the destination substrate. In some embodiments where components comprise ablation layers, the selected components can be forcibly ejected from the selected posts and propelled onto the destination substrate. In embodiments relying on a shear force formed between the selected posts and the selected components, for example by heating and a CTE mismatch between the selected posts and the selected components, the selected components can fall from the selected posts to the destination substrate under the force of gravity.

In some embodiments of the present disclosure, irradiating selected posts comprises irradiating a single post at a time. In some embodiments of the present disclosure, irradiating selected posts comprises irradiating multiple posts at a time. The light source can be a laser and methods of the present disclosure can comprise providing an optical system that can controllably direct a laser beam from the laser to one, or more than one, selected post at a time.

In some embodiments of the present disclosure, each of the posts has a distal end protruding away from the body and the step of contacting each post to a component comprises contacting the distal end of the post to the component to adhere the component to the distal end of the post. Irradiating the selected posts with the light source controllably irradiates the distal end of each selected post or the selected component (e.g., portions of the selected component) to detach the selected component adhered to the selected post from the distal end of the selected post and from the selected post.

In some embodiments, selected components are first selected components, non-selected components are first non-selected components, and the method comprises: providing a destination substrate; transferring the first selected components to first component locations; selecting second selected components from among the first non-selected components, wherein the non-selected posts to which the second selected components are adhered are second selected posts; and transferring the second selected components to second component locations by irradiating the second selected posts through the body with the light to detach the

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second selected components adhered to the second selected posts from the second selected posts. In some embodiments, the components define an array, the first selected components are a first sparse subset of the array, and the second selected components are a second sparse subset of the array.

In some embodiments of the present disclosure, a micro-transfer printing system comprises a stamp comprising a body and spaced-apart posts protruding away from the body and a light source for controllably irradiating each of the posts with light. The body and the posts are substantially transparent to the light. In some embodiments, a component is adhered to each of the posts. In some embodiments, a component is adhered only to each of the non-selected posts. In some embodiments, each component comprises an ablation layer of ablative material that is in contact with the post to which the component is adhered. The ablation layer can be a patterned layer or an unpatterned layer and can be or comprise, for example, any one or more of a layer of metal, a layer of dielectric material, a layer comprising a dye, a layer comprising a black material, and a layer comprising carbon black.

In some embodiments of the present disclosure, the light emitted by the light source is non-visible light and the ablation layer is at least partially transparent to visible light, for example 50% transparent.

In some embodiments of the present disclosure, the micro-transfer printing system comprises an optical system operable to controllably direct light from the light source to the posts. Each of the posts can comprise a distal end away from the body and the optical system can be controllable to irradiate the distal end of one of the posts at a time or to irradiate a distal end of each of multiple ones of the posts at a time.

In some embodiments of the present disclosure, the micro-transfer printing system comprises a motion-control system operable to move the stamp in at least two directions. The motion-control system can be operable to controllably contact the posts to the components to adhere one of the components to each of the posts and remove the stamp from the component source wafer with a component adhered to the distal end of each of the posts.

In some embodiments, a micro-transfer printing system comprises a motion-control system including a motion platform sized and shaped to have a stamp attached or mounted thereto and a light source operable to controllably irradiate the posts with light when the stamp is attached or mounted to the motion platform. The motion-control system is operable to move the stamp in at least two directions. In some embodiments, the stamp comprises a body and spaced-apart posts protruding away from the body.

According to some embodiments of the present disclosure, a method of micro-transfer printing comprises providing a component source wafer having micro-transfer printable components disposed on or in the component source wafer, each micro-transfer printable component comprising a device and an ablation layer disposed on the device, providing a stamp comprising a body and spaced-apart posts protruding away from the body, the posts having a spatial distribution on the body matched to a spatial distribution of the micro-transfer printable components on or in the component source wafer, providing a light source, providing a destination substrate, contacting each of the posts to a micro-transfer printable components to adhere the micro-transfer printable component to the post, thereby forming adhered micro-transfer printable components, removing the stamp with the adhered micro-transfer printable components from the component source wafer, disposing the stamp with

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the adhered micro-transfer printable components in alignment with the destination substrate, irradiating one or more of the posts and the ablation layer of the micro-transfer printable component adhered to each of the one or more of the posts with light from the light source to detach the micro-transfer printable component from the post, thereby forming one or more detached micro-transfer printable components, and removing the stamp from the destination substrate, leaving the one or more detached micro-transfer printable components in contact with the destination substrate. The body and the posts can be substantially transparent to the light.

According to some embodiments, the component source wafer comprises a patterned sacrificial layer defining spaced-apart sacrificial portions and anchors, and the micro-transfer printable components are each disposed over one of the sacrificial portions and physically connected to one of the anchors by a tether, and the steps of contacting each of the posts to the micro-transfer printable components and removing the stamp fractures or separates the tethers or separates the tethers thereby separating the adhered micro-transfer printable components from the source wafer.

The stamp can physically contact the micro-transfer printable components to the destination substrate. The step of irradiating the one or more of the posts can be performed at least partially at the same time as removing the stamp from the destination substrate.

Some methods of the present disclosure can comprise cleaning the one or more of the posts after removing the stamp. Some methods of the present disclosure can comprise patterning the light emitted by the light source prior to the light irradiating the one or more of the posts.

According to some embodiments, the stamp is aligned with the destination substrate at a first position and some methods comprise moving the stamp to a second position in alignment with the destination substrate different from the first position after removing the stamp.

According to some embodiments, the one or more of the posts is a first subset of the posts and some embodiments comprise a second subset of the posts comprises one or more of the posts different from the first subset of the posts. Some methods comprise irradiating the posts of the second subset and the ablation layer of the micro-transfer printable component adhered to each of the posts of the second subset of the posts with second light from the light source to detach the micro-transfer printable component from the post. Such irradiation can be done without contacting the stamp to the substrate again so that the detached micro-transfer printable components were picked up with the micro-transfer printable components that were detached from the first subset of posts.

According to some embodiments, the alignment with the destination substrate is a first alignment and the one or more micro-transfer printable components detached from the posts are one or more first components, and some methods comprise contacting each of the posts to a second micro-transfer printable component of the micro-transfer printable components different from any of the first micro-transfer printable components to adhere the second micro-transfer printable component to the post, thereby forming adhered second micro-transfer printable components, removing the stamp with the adhered second micro-transfer printable components from the component source wafer, disposing the stamp with the adhered second micro-transfer printable components in a second alignment with the destination substrate different from the first alignment, irradiating one or more of the posts and the ablation layer of the second

micro-transfer printable component adhered to the one or more of the posts with second light from the light source to detach the second micro-transfer printable component from the post and removing the stamp from the destination substrate.

According to some embodiments, the ablation layer is a patterned ablation layer.

According to some embodiments, the micro-transfer printable components each comprise an individual encapsulation layer covering the ablation layer and irradiating the one or more of the posts vaporizes at least a portion of the ablation layer thereby detaching the micro-transfer printable component adhered to each of the one or more of the posts.

According to some embodiments, removing the stamp occurs at a sufficient rate such that at least a portion of the encapsulation layer remains adhered to each of the one or more posts.

Some embodiments comprise cleaning the at least a portion of the encapsulation layer remaining from each of the one or more posts.

Some embodiments comprise disposing the ablation layer on the device of each of the micro-transfer printable components in a common patterned deposition.

A component source wafer of the present disclosure can comprise a source wafer having micro-transfer printable components disposed on or in the source wafer, each of the micro-transfer printable components comprising a device and an ablation layer disposed on the device. Some embodiments comprise a patterned sacrificial layer defining spaced-apart sacrificial portions and anchors, and the micro-transfer printable components are each disposed over one of the sacrificial portions and physically connected to one of the anchors by a tether. The ablation layer can be disposed on a side of the device opposite the sacrificial layer. The ablation layer can be a patterned layer or an unpatterned layer. The micro-transfer printable component can comprise layers, for example an encapsulation layer, and the ablation layer can be disposed between layers, for example between the encapsulation layer and the device. The ablation layers can be disposed on or in the devices, for example the device of each of the micro-transfer printable components, and can individually or collectively form a patterned ablation layer over the source wafer. According to some embodiments, the ablation layers disposed on or in the devices of each of the micro-transfer printable components form a continuous, unpatterned ablation layer that extends over the source wafer in an area of the source wafer that includes the micro-transfer printable components, for example spans the micro-transfer printable components.

According to embodiments of the present disclosure, a printed system comprises a destination substrate and a printed component disposed on the destination substrate. The printed component comprises a device, a fractured or separated tether, and at least a portion of a layer of ablation material disposed on a side of the device opposite the destination substrate. An array of printed components can be disposed on the destination substrate. The ablation material can be disposed as a portion of a patterned layer of ablation material.

According to some embodiments, a printed component comprises a device, a fractured or separated tether, and at least a portion of a layer of ablation material disposed in a layer of the device or on a side of the device. The printed component can be disposed on a side of a destination substrate. the ablation material can be disposed as a portion of a patterned layer of ablation material

According to some embodiments of the present disclosure, a method of micro-transfer printing comprises providing a component source wafer having micro-transfer printable components disposed on or in the component source wafer, an encapsulation layer source wafer having individual encapsulation layers disposed on or in the encapsulation layer source wafer, and an ablative material source substrate comprising ablative material, providing a stamp comprising a body and spaced-apart posts protruding away from the body, the posts having a spatial distribution on the body matched to a spatial distribution of the micro-transfer printable components on or in the component source wafer and matched to the spatial distribution of the individual encapsulation layers on the encapsulation layer source wafer, providing a light source, providing a destination substrate, contacting each of the posts to an individual encapsulation layer of the encapsulation layer source wafer to adhere the individual encapsulation layer to the post, and contacting the individual encapsulation layers to the ablative material on the ablative material source substrate such that the ablative material adheres to the encapsulation layer while the individual encapsulation layers are adhered to the posts.

Some embodiments comprise contacting each of the posts with an individual encapsulation layer and ablative material to a micro-transfer printable component of the micro-transfer printable components to adhere the micro-transfer printable component to the ablative material on each post, forming adhered components, removing the stamp with the adhered components from the component source wafer, disposing the stamp and adhered components in alignment with the destination substrate, irradiating one or more of the posts and the ablation layer with electromagnetic radiation to detach the component from the post, and removing the stamp from the destination substrate, leaving the components in contact with the destination substrate, wherein the body and the posts are substantially transparent to the light. The ablative material can be disposed as an unpatterned coating over the ablative material source wafer.

Some embodiments of the present disclosure comprise providing a component source wafer having micro-transfer printable components disposed on or in the component source wafer, wherein the spatial distribution of the posts on the body matches a spatial distribution of the micro-transfer printable components on or in the component source wafer, and contacting the individual encapsulation layer with adhered ablative material to a micro-transfer printable component of the micro-transfer printable components to adhere the micro-transfer printable component to the ablative material, thereby forming adhered micro-transfer printable components.

Some methods of the present disclosure comprise providing a light source, providing a destination substrate, removing the stamp with the adhered micro-transfer printable components from the component source wafer, disposing the stamp with the adhered micro-transfer printable components in alignment with the destination substrate, irradiating one or more of the posts and the ablative material adhered to the micro-transfer printable component adhered to each of the one or more of the posts with light from the light source to detach the micro-transfer printable component from the post, thereby forming one or more detached micro-transfer printable components, and removing the stamp from the destination substrate, leaving the one or more detached micro-transfer printable components in contact with the destination substrate. In embodiments, the body and the posts are substantially transparent to the light.

Some embodiments comprise an individual encapsulation layer and ablative material disposed in contact with the encapsulation layer. Some embodiments comprise a fractured or separated tether extending from the individual encapsulation layer. The encapsulation layer can comprise one or more side walls and a top and the ablative material can be disposed on an interior of the one or more side walls, a bottom side of the top, or both on the interior of the one or more side walls and the bottom side of the top.

Some embodiments comprise a device with ablative material disposed between the encapsulation layer and the device.

Certain embodiments of the present disclosure provide a system and method for micro-transfer printing multiple known-good die at one time from a native source wafer to a destination substrate. Certain embodiments of the present disclosure provide a system and a method for micro-transfer printing components having different characteristics using a single pickup (e.g., and multiple prints).

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, aspects, features, and advantages of the present disclosure will become more apparent and better understood by referring to the following description taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a flow diagram illustrating methods in accordance with some embodiments of the present disclosure;

FIG. 2 is a schematic perspective of a component source wafer, stamp, motion, platform, and optical system illustrating some embodiments of the present disclosure;

FIG. 3 is a schematic cross section of a component source wafer with a component according to illustrative embodiments of the present disclosure;

FIG. 4 is a schematic cross section of component testing on a component source wafer according to illustrative embodiments of the present disclosure;

FIG. 5 is a schematic cross section of an array of selected and non-selected components on a component source wafer according to illustrative embodiments of the present disclosure;

FIG. 6 is a schematic cross section of a stamp picking up components according to illustrative embodiments of the present disclosure;

FIG. 7A is a schematic cross section of a selected component removal from a stamp according to illustrative embodiments of the present disclosure;

FIG. 7B is a detail schematic cross section of a selected component removal from a stamp corresponding to FIG. 7A according to illustrative embodiments of the present disclosure;

FIG. 8 is a schematic cross section of non-selected components printing to a destination substrate according to illustrative embodiments of the present disclosure;

FIG. 9 is a flow diagram illustrating methods in accordance with some embodiments of the present disclosure;

FIG. 10 is a schematic cross section of components printing to a destination substrate according to illustrative embodiments of the present disclosure;

FIG. 11 is a schematic cross section of selected component removal from a stamp according to illustrative embodiments of the present disclosure;

FIG. 12 is a schematic cross section of stamp removal of a non-selected component from a destination substrate according to illustrative embodiments of the present disclosure;

FIG. 13 is a flow diagram illustrating a method in accordance with some embodiments of the present disclosure;

FIGS. 14A-14C are schematic plan views of first and second locations printed to in successive printings on a destination substrate, according to illustrative embodiments of the present disclosure;

FIG. 15 is a flow diagram illustrating methods according to illustrative embodiments of the present disclosure;

FIGS. 16 and 17 are sequential schematic cross sections of a component with ablative material and an encapsulation layer during printing according to illustrative embodiments of the present disclosure;

FIG. 18 is a schematic cross section of a component with an encapsulation layer according to illustrative embodiments of the present disclosure;

FIG. 19 is a schematic cross section of a component with an encapsulation layer according to illustrative embodiments of the present disclosure;

FIG. 20 is a schematic cross section of a printed component and stamp with encapsulation layer according to illustrative embodiments of the present disclosure;

FIG. 21 is a schematic cross section of a printed component and stamp with a partial encapsulation layer according to illustrative embodiments of the present disclosure;

FIG. 22 is a schematic top view of a printable component with an unpatterned ablation layer on the printable component and FIG. 23 is a schematic top view of a printable component with a patterned ablation layer on the printable component according to illustrative embodiments of the present disclosure;

FIG. 24 is a flow diagram illustrating methods according to embodiments of the present disclosure; and

FIG. 25 is a cross section of a stamp post with ablative material and a component source wafer with a printable component illustrating methods according to illustrative embodiments of the present disclosure.

The features and advantages of the present disclosure will become more apparent from the detailed description set forth below when taken in conjunction with the drawings, in which like reference characters identify corresponding elements throughout. In the drawings, like reference numbers generally indicate identical, functionally similar, or structurally similar elements. The figures are not necessarily drawn to scale.

DETAILED DESCRIPTION OF CERTAIN EMBODIMENTS

The present disclosure provides, inter alia, methods and systems for constructing completely functional micro-transfer-printed systems. Such completely functional systems can comprise one or more functional components on a destination substrate, for example a display substrate. Methods and systems in accordance with certain embodiments of the present disclosure enable micro-transfer printing known-good components from a component source wafer to a destination substrate. For example, known-good components can be transferred to a destination substrate by picking up multiple components from the component source wafer with a stamp, removing selected components (e.g., faulty components) from the stamp, and micro-transfer printing the remaining non-selected components to the destination substrate. For example, known-good components can be transferred to a destination substrate by picking up multiple components from the component source wafer with a stamp and micro-transfer printing only selected (e.g., known-good) components to the destination substrate without micro-

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transfer printing non-selected (e.g., faulty) components. Methods and systems in accordance with certain embodiments of the present disclosure enable micro-transfer printing components from a component source wafer to a destination substrate independently from components having at least one different characteristic. Methods and systems in accordance with certain embodiments of the present disclosure enable micro-transfer printing components from a stamp to a destination substrate depending on the location of the components relative to the destination substrate so that different subsets of components adhered to the stamp are micro-transfer printed to different locations or areas of the destination substrate.

Referring to the flow diagram of FIG. 1, the schematic perspective of FIG. 2, and the detail cross section of FIGS. 3-6, in some embodiments of the present disclosure, a method of micro-transfer printing comprises providing in step 100 a component source wafer 20 comprising components 22 disposed on or in component source wafer 20. Components 22 can be micro-transfer printable components 22. In some embodiments, component source wafer 20 comprises a patterned sacrificial layer 66 defining spaced-apart sacrificial portions 68 and anchors 64 and each component 22 is disposed over a sacrificial portion 68 and physically connected to an anchor 64 by a tether 62 (in some embodiments, a plurality of tethers 62, optionally connected to a plurality of anchors 64). A stamp 10 comprising a body 12 and spaced-apart posts 14 each protruding in a direction away from body 12 to a distal end 18 of post 14 is provided in step 110. Posts 14 can be in an array, for example evenly spaced in one or two dimensions (e.g., with equal or unequal spacing in each dimension). Distal end 18 of post 14 is the end of post 14 farthest away from stamp body 12. The positioning of stamp 10 relative to component source wafer 20 can be controlled, for example, by a mechanical motion-control system including motion platform 40 for moving stamp 10 in x, y, and, optionally, z dimensions (e.g., horizontally and, optionally, vertically). In some embodiments, an alternative or additional motion platform for moving component source wafer 20 (e.g., horizontally and, optionally, vertically) is provided. Posts 14 have a spatial distribution on body 12 matched to a spatial distribution of components 22 on component source wafer 20.

In step 120, an optical system 36 comprising an optics controller 38 and light source 30 for controllably irradiating each post 14 with light 32 through body 12 using optics 34 is provided and, in some embodiments, can be positioned relative to stamp 10 by mechanical motion platform 40. Provided light source 30 can controllably irradiate each post 14 with light 32 through body 12. By controllably irradiating each post, it is meant that each of the posts 14 can be irradiated by light 32, or not, depending on whether post 14 is a selected post 15 or a non-selected post 16. That is, when non-selected posts 16 are controllably irradiated by light source 30, it is meant that non-selected posts 16 are not intentionally exposed to any light 32 from light source 30 (ignoring the possibility that a small amount of stray light may be incident on non-selected posts 16). In some embodiments, a light source 30 moves relative to optics 34 to controllably irradiate different selected posts 15. In some embodiments, one or more elements of optics 34 (e.g., one or more mirrors) move relative to a light source 30 to controllably irradiate different selected posts 15. In some embodiments, irradiation of each selected post 15 occurs automatically (e.g., due to automatic motion of one or more elements, such as optics 34, light source 30, stamp 10, component source wafer 20, or destination substrate 70)

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upon a start input being received (e.g., into optics controller 38). Body 12 and posts 14 can be substantially transparent to light 32 emitted by light source 30. Optics controller 38 is shown disposed on optics 34 in FIG. 2, but optics controller 38 can be remotely located and operable to receive and/or send signals, for example by one or more wires (e.g., cables) or wirelessly.

Destination substrate 70 (e.g., as shown in FIG. 8) is provided in step 130 and, in some embodiments, can be positioned relative to stamp 10 by mechanical motion platform 40. Thus, in some embodiments of the present disclosure, mechanical motion platform 40 can move destination substrate 70 relative to stamp 10, can move stamp 10 relative to component source wafer 20, and can move light source 30 and optics 34 relative to stamp 10, or any combination of these. In some embodiments, an alternative or additional motion platform for moving destination substrate 70 (e.g., horizontally and, optionally, vertically) is provided. In some embodiments of the present disclosure, motion platform 40 can be provided in a variety of forms. In some embodiments, motion platform 40 is provided between at least a portion of optical system 36 (e.g., optics 34) and stamp 10. In some embodiments, motion platform 40 is provided such that at least a portion of optical system 36 (e.g., optics 34) is disposed between motion platform 40 and stamp 10. In some embodiments, motion platform 40 surrounds at least a portion of the perimeter of stamp 10. Motion platform 40 can be integrated with stamp 10 or optical system 36, for example.

Referring to FIG. 4, in step 140 each component 22 is tested, for example with test fixture 90, to determine if component 22 is functional (step 141). In some embodiments, testing electrically stimulates components 22 to respond with an electrical or optoelectrical response that is measured. In some embodiments, if a component 22 is not functional (i.e. component 22 is a faulty component) it is selected (a selected component 23) and if a component 22 is functional, it is not selected (a non-selected component 24), as shown in FIG. 5. (In some embodiments, if a component 22 is functional it is a selected component 23 and if a component 22 is not-functional (i.e. component 22 is a faulty component), it is a non-selected component 24.) Results of the test can be stored in memory 39 for example. (For illustration purposes, memory 39 is shown disposed on optics 34 in FIG. 2, but memory 39 can be remotely located and operable to receive and/or send signals, for example by one or more wires (e.g., cables) or wirelessly.) Memory 39 can be connected to optics controller 38 by one or more wires (e.g., cables) or wirelessly. Memory 39 can be part of optical system 36. In step 150 and as shown in FIG. 6, after removing sacrificial material from sacrificial portions 68, stamp 10 is moved by motion platform 40 so that distal end 18 of each post 14 is contacted to a component 22 (for both selected components 23 and non-selected components 24) to adhere a component 22 to distal end 18 of each post 14. Stamp 10 with adhered components 22 is then removed from component source wafer 20 in step 155, breaking (e.g., fracturing) or separating tethers 62 to form separated or broken tethers 63.

Referring to FIG. 7A and the detail of FIG. 7B, in response to test information stored in memory 39, optics controller 38 of optical system 36 controls light source 30 to emit light 32 through body 12 with optics 34 and irradiate each selected post 15 that contacts an adhered corresponding selected component 23 to detach the corresponding adhered selected (e.g., faulty) component 23 from selected post 15, leaving non-selected (e.g., known-good) components 24

adhered to corresponding non-selected posts 16. It is noted that FIGS. 7A and 7B show an example optical system 36 that has a different orientation of optics 34 and light source 30 than the example shown in FIG. 2.

In some embodiments of the present disclosure, selected posts 15 of stamp 10 can be irradiated to remove selected components 23 after moving stamp 10 to a disposal area in a location remote from component source wafer 20 and destination substrate 70 to avoid contamination of component source wafer 20 and destination substrate 70 with faulty selected components 23. In some embodiments, selected components 23 are lightly adhered to a disposal substrate so that irradiated selected components 23 adhere to the disposal substrate and non-selected components 24 that are not irradiated do not adhere to the disposal substrate.

In some embodiments of the present disclosure, selected posts 15 of stamp 10 can be irradiated while posts 14 are in contact with components 22 while components 22 are on component source wafer 20, so that only non-selected components 24 are adhered to non-selected posts 16 when stamp 10 is removed from component source wafer 20. In some embodiments, the steps of irradiation and removal of stamp 10 from selected components 23 occur at the same time, occur partially at the same time, or overlap in time. By removing stamp 10 (with non-selected components 23 adhered to non-selected posts 16) from component source wafer 20 during the irradiation, selected components 23 are prevented from re-adhering to selected posts 15 after the irradiation is complete.

Referring to FIG. 8, in some embodiments non-selected components 24 on non-selected posts 16 are contacted to destination substrate 70 to adhere non-selected components 24 to destination substrate 70 in step 190 and stamp 10 is removed from destination substrate 70 in step 200 with no components 22 adhered to stamp 10. Thus, only components 22 that are tested and known to be good are transferred to destination substrate 70. In some embodiments, selected components 23 are in contact with destination substrate 70 during the irradiation process. In some embodiments, selected components 23 are not in contact with destination substrate 70 during the irradiation process. For example, selected components 23 can be within 20 μm (e.g., within 10 μm , within 5 μm , within 2 μm , or within 1 μm) of destination substrate 70, but not in contact, during irradiation. Destination substrate 70 is shown coated with optional adhesive layer 72 such that non-selected components 24 directly contact adhesive layer 72. In some embodiments, no such adhesive layer is present (e.g., such that non-selected components 24 are directly printed onto destination substrate 70).

In some embodiments, after known-good components 22 are micro-transfer printed to destination substrate 70, any components 22 determined to be missing (step 220) can be printed by repeating the printing process until no components 22 are missing and the process is done (step 230). For example, one or more missing components 22 can be printed by only picking up and testing a single component 22 at a time and printing the single component 22 (e.g., if it is a functional component 22).

In some embodiments, ablation occurs during irradiation that leads to component 22 separation. Selected components 23 can be forcibly ejected from selected posts 15 due to ablation (e.g., of an ablation layer 50 of selected components 23 disposed in contact with selection posts 15). In some embodiments, selected components 23 are detached from selected posts 15 by a shear force that forms between selected posts 15 and selected components 23 when the

selected posts 15 and selected components 23 have a CTE mismatch and are, for example, heated (e.g., by irradiation). Non-selected components 24 on non-selected posts 16 are not detached from the non-selected posts (e.g., because no differential thermal expansion occurs between the non-selected posts 16 and non-selected components 24) and are not adhered to the substrate when stamp 10 is removed from the substrate. A CTE mismatch can occur with or without the presence of an ablation layer 50 in components 22.

Optionally, after selected posts 15 are irradiated to detach selected components 23, selected posts 15 can be examined in step 170 to verify that selected components 23 are indeed detached (step 180). Such a determination can be made using an optical camera and one or more image recognition techniques, for example. If any selected components 23 are still attached to selected posts 15, irradiation step 160 can be repeated for selected posts 15 with attached selected components 23 (or all selected posts 15). In step 150, missing components 22 are determined and additional components 22 from a component source wafer 20 that are tested and known to be good can be printed to locations on destination substrate 70 that were not printed with non-selected components 24 in step 190.

The method illustrated in FIG. 1 comprises removing selected (faulty) components 23 from stamp 10 before printing non-selected (known-good) components 24 to destination substrate 70. In some embodiments of the present disclosure, selected (known-good) components 23 in contact with destination substrate 70 can be removed from stamp 10 and non-selected (faulty) components 24 removed with stamp 10 from destination substrate 70. In such embodiments, if a component 22 is functional it is selected (a selected, known-good component 23); if a component 22 is not functional, it is not selected (a non-selected faulty component 24). This selection criterion is the inverse of the selection criterion for the illustrative embodiment in FIG. 1.

Referring to FIG. 9, in some embodiments of the present disclosure, steps 100-150 are performed as described above. However, rather than removing selected (non-functional) components 23 from selected posts 15 of stamp 10, for example as in step 160 of FIG. 1, all components 22 adhered to posts 14 of stamp 10 are contacted or located closely adjacent to or above destination substrate 70, as shown in step 191 and FIG. 10. In step 160 and as shown in FIG. 11, distal ends 18 of selected posts 15 in contact with selected (functional) components 23 are irradiated to detach selected components 23 from distal ends 18 of selected posts 15. Stamp 10 is then removed from destination substrate 70 with non-selected (non-functional) components 24 in contact with non-selected posts 16 in step 201 and as shown in FIG. 12. The irradiation and removal steps 160, 201 can be executed simultaneously or overlap in time to facilitate detachment of selected (known-good) components 23 and removal of non-selected (faulty) components 24. In some embodiments, after known-good components 22 are micro-transfer printed to destination substrate 70, any components 22 missing from destination substrate 70 can be determined in step 220 and printed by repeating the printing process including step 150. For example, one or more missing components 22 can be printed by only picking up and testing a single component 22 at a time and printing the single component 22 (e.g., if it is a functional component 22).

In some embodiments, selected components 23 are in contact with destination substrate 70 during the irradiation process. In some embodiments, selected components 23 in contact with destination substrate 70 and selected components 23 are removed from selected posts 15 during irradiation.

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tion, so that the steps of irradiation and removal of stamp 10 from selected components 23 occur at the same time, occur partially at the same time, or overlap in time. By removing selected posts 15 (with the stamp 10) from selected components 23 during the irradiation, selected components 23 are prevented from re-adhering to selected posts 15 after the irradiation is complete. In some embodiments, selected components 23 are adjacent to but not in contact with destination substrate 70 so that selected components 23 are detached from selected posts 15 and selected components 23 travel (e.g., drop) from selected posts 15 to destination substrate 70. For example, selected components 23 can be within 20 μm (e.g., within 10 μm , within 5 μm , within 2 μm , or within 1 μm) of destination substrate 70, but not in contact, when detached.

In some embodiments, an ablation layer 50 is ablated to detach selected components 23 from selected posts 15. Selected components 23 can be forcibly ejected from selected posts 15 and propelled onto destination substrate 70. In some such embodiments, a gap between selected components 23 and destination substrate 70 can enable the transfer of selected components 23 to destination substrate 70 without re-adhesion of selected components 23 to selected posts 15. Re-adhesion can result in a failed transfer. In some embodiments, shear force formed between selected posts 15 and selected components 23, for example by heating and a CTE mismatch between selected posts 15 and selected components 23, causes detachment of selected components 23 from selected posts 15. Selected components 23 can contact destination substrate 70 to enable adhesion of selected components 23 to destination substrate 70, promoting transfer. A CTE mismatch can occur with or without the presence of an ablation layer 50 in components 22.

Stamp 10 can then be cleaned in step 210. As an example, stamp 10 can be cleaned by contacting non-selected components 24 to an adhesive cleaning surface in a disposal area (e.g., a sticky tape). As an example, stamp 10 can be cleaned by irradiating distal ends 18 of non-selected posts 16 in a suitable disposal location to remove non-selected components 24 from non-selected posts 16. In some embodiments, after known-good components 22 are micro-transfer printed to destination substrate 70, any components 22 determined to be missing (step 220) can be determined in step 150 and printed by repeating the printing process until no components 22 are missing and the process is done (step 230). For example, one or more missing components 22 can be printed by only picking up and testing a single component 22 at a time and printing the single component 22 (e.g., if it is a functional component 22).

According to some embodiments of the present disclosure, and as shown in FIG. 7A, a micro-transfer printing system 99 comprises a stamp 10 that comprises a body 12 and spaced-apart posts 14 protruding away from body 12. A light source 30 can controllably (e.g., selectively) irradiate each selected post 15 with light 32. (Light 32 can generally be any electromagnetic radiation, such as, for example, visible light, ultraviolet light, or infrared light.) In some embodiments, a component 22 (either a selected component 23 or a non-selected component 24) is adhered to each post 14. Body 12 and posts 14 are substantially transparent to light 32 emitted by light source 30. By substantially transparent it is meant that light 32 from light source 30 can pass through body 12 and posts 14 with sufficient luminance to detach components 22 from distal end 18 of selected posts 15. As a non-limiting example, a body 12 and posts 14 that are substantially transparent to light 32 from a light source 30 can be at least 70% (e.g., at least 80% or at least 90%)

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transparent. Posts 14 and body 12 can be made from a same material or comprise different materials. Irradiation of selected posts 15 can irradiate a distal end 18 of selected posts 15, can irradiate selected components 23 adhered to distal ends 18 of selected posts 15, can irradiate a portion of selected components 23 adhered to distal ends 18 of selected posts 15, can irradiate a layer of selected components 23 adhered to distal ends 18 of selected posts 15, or any combination of these. Irradiating a selected post 15 with an adhered selected component 23 detaches (e.g., causes detachment of) the selected component 23 from the distal end 18 of the selected post 15.

In some embodiments, components 22 comprise an ablation layer 50 of ablative material 52 in contact with each post 14 to which a component 22 is adhered (e.g., adhered to distal end 18 of selected post 15). Ablative material 52 is chosen to absorb light 32 emitted from light source 30, for example to selectively absorb light 32 from light source 30, and, in some embodiments, vaporizes in response to the absorption. Ablative material 52 can be at least partially transparent to visible light and light 32 emitted from light source 30 can be invisible, for example infra-red or ultraviolet. Thus, in some embodiments, light 32 emitted by light source 30 is non-visible light and ablation layer 50 is at least partially transparent to visible light, for example at least 30% (e.g., at least 40%, at least 50%, at least 70%, at least 80%, or at least 90%) transparent to visible light. Ablation of ablation layers 50 detaches (e.g., assists in detaching along with stamp 10 motion) selected components 22 from posts 15.

In some embodiments, stamp 10 is a visco-elastic stamp 10, for example a PDMS (polydimethylsiloxane) stamp 10. Body 12 and posts 14 can be made from a same material (e.g., PDMS) and have different mechanical properties (e.g., due to a different composition of the material in the body 12 and posts 14). In some embodiments, light source 30 is a laser. In some embodiments, an optical system 36 (e.g., comprising optics 34, light source 30, and optics controller 38) controllably directs light 32 from light source 30 to one or more posts 14, e.g., selected posts 15. In some embodiments, optical system 36 (light source 30, optics controller 38, and optics 34) is controllable to irradiate a distal end 18 of one selected post 15 at a time (e.g., using one or more wave guides, lenses, or mirrors). In some embodiments, light source 30 or optics 34 move, and subsequently light source 30 emits light 32, during controlled irradiation such that each emission of light 32 irradiates only one selected post 15 due to alignment between light source 30, optics 34, and one selected post 15. In some embodiments, optical system 36 is controllable to irradiate distal ends 18 of multiple selected posts 15 at a time (e.g., using one or more wave guides, lenses, beam splitters, or mirrors). In some embodiments, light source 30 or optics 34 move, and subsequently light source 30 emits light 32, during controlled irradiation such that each emission of light 32 irradiates multiple selected posts 15 due to alignment between light source 30, optics 34, and multiple selected posts 15 (e.g., where multiple selected posts 15 are only a portion or all of selected posts 15).

In some embodiments, micro-transfer printing system 99 comprises memory 39. In some embodiments, memory 39 can store a mapping of selected components 23 and non-selected components 24. A mapping can correspond to locations of selected components 23 and non-selected components 24 on component source wafer 20, for example. In some embodiments, a mapping of selected components 23 and non-selected components 24 is formed or determined

based, at least in part, on input from test fixture 90. In some embodiments, a mapping of selected components 23 and non-selected components 24 is formed or determined based, at least in part, on known locations of a first set of components 22 and a second set of components 22, the sets disposed on or in a component source wafer 20 and the second set having at least one characteristic different from the first set. In some embodiments, a mapping of selected components 23 and non-selected components 24 is formed or determined based, at least in part, on known locations of a first set of components 22 and a second set of components 22 on a destination substrate 70 after their printing. A mapping can be used by optics controller 38 for controllably irradiating selected posts 15. Irradiating selected posts 15 can occur automatically (e.g., by automatic and controlled movement of optics 34 and/or light source 30 relative to stamp 10), for example, when using a mapping.

In some embodiments, micro-transfer printing system 99 comprises a motion-control system (e.g., including motion platform 40) for moving stamp 10 (e.g., relative to component source wafer 20) and, optionally, relative to at least some portions of optical system 36. In some embodiments, a motion-control system can move stamp 10 between a location corresponding to component source wafer 20 (e.g., over component source wafer 20) and a location corresponding to destination substrate 70 (e.g., over destination substrate 20) and, optionally, vertically, for example when in the location corresponding to the component source wafer 20 or the destination substrate 70. In some embodiments, a motion-control system can also move stamp 10 to a disposal area (e.g., with a disposal substrate in the disposal area). In some embodiments, stamp 10 is mounted or attached to a motion-control system (e.g., a motion platform 40 of the motion-control system). Stamp 10 can be mounted or attached to a motion-control system by, for example, one or more clamps, one or more fasteners, one or more braces, or adhesive. In some embodiments, micro-transfer printing system 99 comprises a component source wafer 20 comprising micro-transfer printable components 22. A motion-control system can be adapted to controllably contact posts 14 to components 22 to adhere a component 22 to each post 14 and remove stamp 10 from component source wafer 20 with each component 22 adhered to a distal end 18 of a post 14.

In some embodiments, each post 14 comprises a distal end 18 that protrudes away from body 12, components 22 are adhered to distal end 18 of selected posts 15, and light source 30 controllably irradiates distal end 18 of each selected post 15.

Component source wafer 20 can be any wafer suitable for the assembly or construction of components 22 on patterned sacrificial portions 68, for example glass, mono-crystalline semiconductor (e.g., silicon) or compound semiconductor (e.g., GaN or GaAs), quartz, sapphire, or ceramic. Component source wafers 20 can have a diameter, for example, greater than or equal to 10 cm (e.g., greater than or equal to 15 cm, 20 cm, 25 cm, 30 cm, 40 cm, or 100 cm). In some embodiments, a component source wafer 20 has a diameter that is less than or equal to 200 cm. Suitable component source wafers 20 are found in the semiconductor, integrated circuit, and display industries and can be processed, for example, using photolithographic methods and materials. Patterned sacrificial layer 66 can be a patterned oxide or nitride layer (such as silicon oxide or silicon nitride) that is differentially etchable from the remainder of component source wafer 20 or can be a layer comprising designated portions in a layer of component source wafer 20 (e.g.,

etchable portions under components 22). In some embodiments, component source wafer 20 comprises an anisotropically etchable crystalline material (such as silicon) that can be anisotropically etched to remove material from sacrificial portions 68 to release components 22 from component source wafer 20, leaving components 22 each attached by one or more tethers 62 to one or more anchors 64.

Referring back to FIG. 3, components 22 can be any of a wide variety of devices, such as, for example but not limited to, electronic, optical, optoelectronic, mechanical, or piezoelectric devices. Components 22 can be optically emissive or responsive and can be light emitters (such as LEDs), light sensors (such as photodiodes), lasers, or electrical jumpers. Components 22 can be integrated circuits (for example CMOS, bipolar, or mixed circuits) and comprise electronically active or passive elements or both. Components 22 can be constructed using photolithographic methods and materials. Components 22 can have, for example, at least one of a width, length, and height from 2 μm to 1000 μm (for example 2 to 5 μm , 5 to 10 μm , 10 to 20 μm , 20 to 50 μm , 50 μm to 100 μm , 100 μm to 250 μm , 250 μm to 500 μm , or 500 μm to 1000 μm). Components 22, for example, can have a doped or undoped semiconductor structure 82 substrate thickness from 2 μm to 50 μm (for example from 2 to 5 μm , 5 to 10 μm , 10 to 20 μm , or 20 to 50 μm). Components 22 can have a length greater than width, for example having an aspect ratio greater than or equal to 2 (for example greater than or equal to 4, 8, 10, 20, or 50). Components 22 can comprise component contact pads 83 that are adjacent to the ends of components 22 along the length of components 22 to provide electrical contact to components 22. Components 22 can comprise a patterned dielectric layer 87 to provide electrical insulation and electrodes 84 to provide electrical connection to component contact pads 83. An encapsulation layer 88 (for example a second dielectric layer of silicon dioxide or nitride) can protect components 22 and, optionally, provide a tether 62. An optional ablation layer 50 of ablative material 52 can be provided, for example using photolithographic process and materials, on a surface of components 22 that is contacted by distal end 18 of posts 14.

In some embodiments, subsets of components 22 disposed on or in component source wafer 20 have one or more different characteristics that are not merely natural variation within manufacturing tolerances of components 22. A characteristic that is different between two components 22 can be, for example, size, shape, an optical property, an electronic property (e.g., piezoelectricity), or a mechanical property. For example, a different characteristic can be emission wavelength (e.g., if components 22 are light emitters), circuit design (e.g., if components 22 are controllers, such as micro-controllers), or properties that are sensed or sensitivity to those properties (e.g., if components 22 are sensors). If components 22 disposed on or in component source wafer 20 are light emitters, a characteristic that is different can be, for example, color (e.g., emission wavelength), hue, tint, shade, brightness, efficiency, or angular distribution of emitted light. Selected ones of components 22 can be selected based on a characteristic that they have, with non-selected ones of components 22 having at least one different characteristic. In some embodiments, non-selected components 24 having a different characteristic are micro-transfer printed in a later step (e.g., after moving a position of stamp 10 having non-selected components 24 still disposed thereon relative to destination substrate 70). In some embodiments, selected components 23 are not uniform, for example selected components 23 can comprise components 22 hav-

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ing different characteristics. For example, selected components 23 can include two or more colors of light-emitting diodes.

A first set of components 22 disposed on or in component source wafer 20 can be interspersed with (or adjacent to) a second set of components 22 disposed on or in component source wafer 20 that has at least one different characteristic. In some embodiments, component source wafer 20 is fabricated having a known distribution of a first set of components 22 and a second set of components 22, the first set of components 22 having at least one characteristic different from a characteristic of the second set of components 22. Selected components 23 can be or comprise either the first set or the second set (with non-selected components 24 being or comprising the other set) (e.g., independent of whether selected components 23 and/or non-selected components 24 comprises one or more faulty components 22). A mapping can be formed or determined based on the known distributions of the first set and the second set and, for example, input into memory 39 in order to micro-transfer print the first set or the second set independent of the other set (e.g., using steps described above). Components 22 having different characteristics can be fabricated on a single component source wafer 20 (as opposed to multiple component source wafers 20) in order to more efficiently utilize valuable material and/or reduce manufacturing steps, thereby reducing costs. For example, different color light-emitting-diodes can be fabricated on a single component source wafer 20 or different integrated circuits can be fabricated on a single component source wafer 20.

In some embodiments, subsets of components 22 adhered to stamp 10 are repeatedly selected and transferred to destination substrate 70. For example, referring to flow diagram FIG. 13, an array of components 22 can be picked up by stamp 10 in step 150 and moved by motion platform 40 to a location with respect to destination substrate 70 in step 205, for example components 22 adhered to stamp 10 are contacted or located closely adjacent to and above destination substrate 70. Selected components 23 representing a subset of components 22 adhered to stamp 10, for example a sparse array of components 22, are selected in step 195 and transferred to first locations 74 on destination substrate 70 by irradiation in step 160, for example as described above. (The selection step 195 can be done at any convenient time, for example, but not limited to, before stamp 10 is moved.) If all of components 22 are transferred and none remain adhered to stamp 10, the process is completed and can be repeated by picking up a new set of components 22 from component source wafer 10 in step 150. If some components 22 remain adhered to stamp 10 (e.g., some of the components were non-selected components 24 during the first printing), the process is repeated by moving stamp 10 to a new location (such that a second subset of components 22 are in second locations 76) over destination substrate 70 (step 205), a different subset of components 22 adhered to stamp 10 is selected (step 195) and transferred to destination substrate 70 (step 160). Subsets of components 22 disposed on stamp 10 (and selected as selected components 23 in successive printing operations) can be interspersed or separated (e.g., adjacent). Second locations 76 on destination substrate 70 can be adjacent, disjointed, or overlapping to first locations 74 in which a first subset of components 22 have already been printed, as shown, for example, in FIG. 14A, FIG. 14B, and FIG. 14C, respectively. For example, a first subset of components 22 in a first locations 76 can be interspersed with a second subset of components 22 disposed in a second locations 76. A

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distance between second locations 76 and first locations 74 can be less than a characteristic separation of a first subset of components 22 that have been disposed in first locations 74.

Thus, components 22 can be distributed in a variety of arrangements on destination substrate 70 different from the arrangement of components 22 on stamp 10 with multiple printing steps and without having to pick up additional components 22 from component source wafer 20, thereby improving the printing throughput and print location flexibility. For example, a 4x4 array of components 22 can be picked up by stamp 10 from component source wafer 10, a first 2x2 subset of the 4x4 array is selected and transferred to first locations 74 on destination substrate 70, then a second 2x2 subset of the remaining twelve components 22 in the 4x4 array is selected and transferred to second locations 76 on destination substrate 70, then a third 2x2 subset of the remaining eight components in the 4x4 array is selected and transferred to third locations on destination substrate 70, and then the remaining four components in the 4x4 array are selected and transferred to fourth locations on destination substrate 70. If the 2x2 arrays comprise, for example, every other component 22 of the 4x4 array of components 22 in one or two dimensions, then the 2x2 arrays are sparse and the printed area of destination substrate 70 can be larger than the area of the 4x4 array, resulting in geometric magnification of the 4x4 printed area on destination substrate 70 with respect to the area of component source wafer 10 from which the 4x4 array of components 22 was picked up. In some embodiments, the arrangement or number of selected components 23 transferred to destination substrate 70 is different in different transfer steps. By performing a single component pick up from the component source wafer 20 and four printing steps, throughput is improved.

Test fixture 90 can be an electronic, mechanical, optical, or combination fixture. Generally, test fixture 90 can include any combination of elements that senses a response from components 22. In some embodiments, test fixture 90 provides power to components 22 for testing purposes. Test fixture 90 can be constructed and arranged to test only one component 22 or a plurality of components 22 at a time. For example, test fixture 90 can be a bed-of-nails electronic probe with circuits for providing electrical power to components 22 through electrodes 84 and component contact pads 83 and electronic or optical sensing circuits for sensing and measuring a response of components 22. In some embodiments, component source wafer 20 comprises wires (electrical conductors) electrically connected to components 22 through electrodes 84 and component contact pads 83 and controlled by test fixture 90, for example as shown in FIG. 4. The wires can be routed over or under tethers 62 or form a portion of tethers 62 and/or formed over exposed portions of sacrificial portions 68 and subsequently removed (e.g., by unpatterned or patterned etching) before pickup by stamp 10. Examples of such wires are shown in FIGS. 3 and 4, where wires 83 connected to contact pads 83 are exposed on a portion of sacrificial portion 68 and extending past anchor 64, thereby allowing for a closed circuit to be formed for testing. Additional examples of such wires are described in U.S. Pat. Nos. 9,923,133 and 9,142,468, both entitled Structures and methods for testing printable integrated circuits. Test fixture 90 can comprise a computer for controlling components 22 and measuring, analyzing, reporting, and storing test information and results in memory 39.

Testing with test fixture 90 can be done either before, or after, sacrificial material in sacrificial portion 68 is removed, e.g., by etching.

Motion platform 40 can be a computer-controlled electro-mechatronic assembly, for example comprising stepper motors for providing multi-axis movement of the platform. Motion platform 40 can comprise a transparent structure (for example a glass or transparent polymer plate) in a fixture for holding stamp 10 and allowing light 32 to pass through the transparent structure to enter stamp 10. Suitable motion platforms 40 are commercially available or can be adapted for use in a micro-transfer printing system 99.

Light source 30 can be a laser that emits laser light 32 (e.g., into optics 34). Optics 34 can comprise, for example, one or more of one or more mirrors, one or more refractive lenses, one or more diffractors, one or more acousto-optic modulators (AOMs), one or more electro-optic modulators (EOMs), one or more beam splitters, and one or more rotating polygonal mirrors to control emitted light 32. For example, light 32 from light source 30 can be scanned over the back surface of stamp 10 and posts 14 and temporally controlled to irradiate any particular selected post 15 (or group of selected posts 15), or not by a real-time electronic/computer controller. Optics controller 38 can receive information from test fixture 90 to specify selected components 23 and selected posts 15. For example, a mapping of selected component 23 locations and non-selected component 24 locations can be formed based, at least in part, on input from test fixture 90, and used by optics controller 38 for controllably irradiating selected posts 15. Suitable or adaptable examples of optical systems 36 and light-control methods and devices are known in the art. In some embodiments, at least some elements of optical system 36 can be moved by motion platform 40 relative to stamp 10 to align light 32 emitted by light source 30 with selected posts 15 and selected components 23. In some such embodiments, light 32 is mechanically scanned over the selected posts 15. Hence, in some embodiments, single selected posts 15 are irradiated at a time to sequentially detach selected components 23. In some embodiments, more than one selected post 15 is irradiated at a time, for example using optics 34 to divide a laser beam (e.g., light 32) into multiple beams. In some embodiments, light source 30 is constructed and disposed such that no optics are needed to controllably irradiate each of the posts 14 in stamp 10. For example, if light source 30 is disposed over stamp 10 and has a small beam width, light source 30 alone can be sufficient to provide controllable irradiation of posts 14 (e.g., by movement of stamp 10 or light source 30).

Stamps 10 having protruding posts 14 used for micro-transfer printing that can be used in systems and methods described herein are described in U.S. Pat. No. 9,412,727 entitled Printing transferable components using microstructured elastomeric surfaces with pressure modulated reversible adhesion. Such stamps 10 can comprise PDMS (polydimethylsiloxane with or without an additive, such as Dow Sylgard 184 Elastomer Base and Curing Agent by Dow Corning Corporation of Auburn, Mich.). Stamp 10 can be made by providing a photolithographically defined mold structure that holds a support in alignment with a stamp mold. The stamp mold can provide a body cavity and one or more structured cavities (e.g., defining posts 14). A liquid curable material is injected into the mold cavity and the assembly is subjected to heat to cure the liquid curable material to form the layer corresponding to the mold. The mold is removed from the mold structure and the stamp 10 removed from the mold.

Stamp body 12 can have a range of thicknesses from 0.50 μm to 1000 μm (e.g., 200 μm). Posts 14 can have a length ranging from 5 μm to 100 μm (e.g., 20 μm), and a height-to-width ratio of 1:4 to 4:1 (or, in some embodiments, more than 4:1). Posts 14, for example, can have a size that is larger or smaller than, or matched to, the size or area of components 22. Additionally, posts 14 can have a shape (in cross-section) that is different than the shape of a contact surface of components 22 or a shape that corresponds to a shape of a contact surface of components 22. Stamp 10 can be provided on a support (not shown in the Figures for simplicity), for example glass, soda-lime glass, borosilicate glass, Pyrex, metal, ceramic, polymer, or a semiconductor (e.g., a wafer or portion of a wafer). The support can have a thickness ranging from 0.5 mm to 10 mm. These ranges and values are illustrative and not limiting and other materials and sizes are included in certain embodiments. Systems comprising motion platforms 40 for micro-transfer printing components 22 from a component source wafer 20 to a destination substrate 70 have been constructed and used to make a wide variety of applications, including, for example active-matrix color displays with pixel controllers and inorganic LEDs.

Components 22 can be at least partially coated with an ablative material 52 in an ablation layer 50. Ablative material 52 can absorb light 32 emitted from light source 30 and, in some embodiments, vaporizes (e.g., generates a plasma) that provides pressure pushing components 22 away from distal end 18 of selected posts 15 to detach (e.g., assist in detaching along with stamp 10 motion) components 22 from selected posts 15 (step 160). Not all of the ablative material 52 is necessarily removed when irradiated by light 32. Ablation layer 50 can be a patterned layer or an unpatterned layer and can be a layer of metal, a layer of dielectric material, a layer comprising a dye, a layer comprising a black material, or a layer comprising carbon black. In some embodiments, ablative material 52 is a dielectric, polymer, or resin and can comprise a dye or other light-absorbing material such as carbon black. Ablative material 52 can be coated, for example, spin coated, spray coated, or hopper coated, and, in some embodiments, patterned using photolithographic patterning methods. Ablative material 52 can be a photoresist material. The light-absorbing material can be matched to light 32 so that the light-absorbing material selectively and efficiently absorbs a frequency of light 32 emitted from light source 30. The frequency of light 32 emitted from light source 30 can generally be any electromagnetic radiation, such as, for example, visible light, ultra-violet light, or infra-red light. In some embodiments, ablative material 52 is substantially transparent to visible light, so that visible light emitted from component 22 can pass through ablation layer 50. In some embodiments, ablative material 52 absorbs visible light. In some embodiments, ablative material 52 is a metal, for example, gold, silver, or aluminum metal and can be part of a patterned circuit on a surface of components 22.

In some embodiments of the present disclosure, light 32 that irradiates selected posts 15 can irradiate distal ends 18 of selected posts 15 or can irradiate components 22 (e.g., portions of components 22 or one or more layers of or on components 22) or any combination of such elements. Light 32 absorbed by any one or both of the distal ends 18 of selected posts 15 and components 22, can heat one or both of the distal ends 18 of selected posts 15 and components 22. If the CTEs of various materials are different, when the materials are heated a shear force will be present between the materials with different CTEs as the different materials

expand by different amounts. This shear force, if present between distal ends 18 of selected posts 15 and selected components 23 (e.g., portions of selected components 23) can cause (e.g., assist along with stamp 10 motion) selected components 23 to detach from distal ends 18 of selected posts 15. If only the distal ends 18 of selected posts 15 are heated by light 32, then expansion of the distal ends 18 can cause (e.g., assist along with stamp 10 motion) selected components 23 to detach from distal ends 18.

According to some embodiments of the present disclosure and as illustrated in FIGS. 8, 10-12, 16-21, a printed component 26 comprises a device 82 (e.g., comprising semiconductor structure 82), a broken (e.g., fractured) or separated tether 63 physically connected to device 82, and at least a portion 51 of a layer 50 of ablative material 52 disposed in a layer of device 82 or on a side of device 82. Printed component 26 can be disposed upon (for example, micro-transfer printed on) destination substrate 70. FIG. 3 illustrates component 22 on component source wafer 20 before component 22 is micro-transfer printed to destination substrate 70 with stamp 10 to provide printed component 26. As discussed above components 22 can be removed from stamp 10 before printing components 22 to destination substrate 70. In some embodiments, all components 22 adhered to posts 14 are transferred (e.g., micro-transfer printed using stamp 10) to destination substrate 70. According to some embodiments, printed components 26 do not comprise any ablative material 52 and any ablative material 52 is removed from a printable component 22 as a consequence of a micro-transfer printing process and corresponding laser ablation. In some embodiments, printed components 26 do comprise at least a portion 51 of a layer 50 of ablative material 52 even after laser ablation, for example ablative material 52 that is not ablated during a micro-transfer printing and laser exposure process. Ablative material 52 can be disposed in a layer 50 on device 82, in device 82, or on a side of device 82.

According to some embodiments of the present disclosure and as illustrated in FIGS. 10-12, a printed system 92 comprises a destination substrate 70 and one or more printed components 26 disposed on destination substrate 70. Each printed component 26 can comprise a device 82, a broken (e.g., fractured) or separated tether 63, and at least a portion 51 of a layer 50 of ablative material 52 disposed on a side of device 82 opposite destination substrate 70. The printed components 26 can be disposed (e.g., micro-transfer printed) on destination substrate 70 in an array.

According to some embodiments of the present disclosure and as illustrated in FIG. 3, a component source wafer 20 comprises a source wafer having micro-transfer printable components 22 disposed on or in the component source wafer 20. Each micro-transfer printable component 22 comprises a device 82 (e.g., a semiconductor structure 82) and an ablation layer 50 disposed on or in each device 82. The component source wafer 20 can comprise a patterned sacrificial layer 66 defining spaced-apart sacrificial portions 68 and anchors 64. The components 22 are each disposed over a sacrificial portion 68 and physically connected to an anchor 64 by a tether 62. In some embodiments, ablation layers 50 disposed on or in device 82 form a continuous, unpatterned ablation layer 50 that extends over component source wafer 20 in an area of component source wafer 20 that includes components 22. In some embodiments, ablation layers 50 disposed on or in device 82 form a patterned ablation layer 50 over the source wafer, for example patterned only on devices 82 or as part of components 22.

Ablative material 52 can be disposed and patterned (if desired) on device 82 by photolithographic means such as evaporative deposition and patterning with photoresist, with inkjet deposition, with lamination, or with coating such as spin coating. In some embodiments, ablative material 52 is picked up by posts 14 from a supply (e.g., a coated substrate) and then contacted to device 82 on component source wafer 20.

In some embodiments, as illustrated in FIG. 3, ablation layer 50 is disposed on a side of device 82 opposite sacrificial layer 66. In some embodiments, for example as shown in FIGS. 18 and 19, micro-transfer printable device 82 comprises layers, for example encapsulation layer 80, and ablation layer 50 is disposed between layers, for example between encapsulation layer 80 and device 82. For example, an encapsulation layer 80 can be disposed over ablation layer 50. By disposing ablation layer 50 under an encapsulation layer 80, a distal end 18 of posts 14 of stamp 10 are protected from ablative material 52 when ablative material 52 is ablated, for example by light 32 emitted from light source 30 (e.g., laser 30, shown in FIG. 7A). Light 32 can be uniform and flood an area or can be patterned, either spatially (e.g., in a raster scan) or temporally (e.g., pulsed instead of continuous). When ablative material 52 absorbs light 32, it becomes energetic (e.g., hot) and dissociated from ablation layer 50, for example as shown in FIG. 17. Post 14 can comprise a relatively soft material, such as an elastomer. If post 14 is exposed to the energetic particles of ablative material 52, post 14 can be degraded, for example pitted. By disposing encapsulation layer 80 between ablation layer 50 and post 14, as shown in FIG. 16, post 14 is protected from energetic particles of ablative material 52, as shown in FIG. 17 by encapsulation layer 80.

As shown in FIGS. 16, 17, and 19, in some embodiments, encapsulation layer 80 is disposed only on a top side of device 82 over ablation layer 50. In some embodiments illustrated in FIGS. 18, and 20-21, encapsulation layer 80 is disposed on or adjacent to one or more sides of device 82 or one or more sides of layers disposed on component 22 over ablation layer 50. FIG. 18 illustrates a generic component 22 with device 82, encapsulation layer 80, ablation layer 50, and broken (e.g., fractured) or separated tether 63. FIG. 19 illustrates a component 22 (such as a horizontal LED) with encapsulation layer 80 and tether 62 on component source wafer 20. FIG. 20 illustrates stamp 10 removal with encapsulation layer 80 from component 22 after or during laser ablation. Post 14 is protected from ablative material 52 particles by encapsulation layer 80. As shown in FIGS. 18 and 20, ablation layer 50 can extend onto sides of device 82 as well as a top side opposite component source wafer 20 and destination substrate 70. As shown in FIG. 21, encapsulation layer 80 can be broken (e.g., fractured) (and can be designed to break (e.g., fracture)) by ablating ablation layer 50 so that stamp 10 retrieves only a portion of encapsulation layer 80. Post 14 can be cleaned by pressing post 14 against a cleaning surface, for example a sticky substrate surface (e.g., a tape) to remove any encapsulation layer 80 material or ablative material 52.

In some embodiments, a stamp 10 picks up an encapsulation structure (encapsulation layer 80) alone by itself, picks up ablative material 52 on the encapsulation layer 80, and then contacts component 22 on component source wafer 20 to pick up component 22. The pickup can be enhanced if the ablative material 52 is slightly adhesive. Component 22 is then disposed on or near destination substrate 70, ablative material 52 ablated to separate component 22 from encap-

sulation layer 80 and deposit component 22 on destination substrate 70, and encapsulation layer 80 removed, for example by a cleaning step.

According to some embodiments of the present disclosure, for example as shown in FIG. 15, a method of micro-transfer printing comprises providing a component source wafer 20 having micro-transfer printable components 22 disposed on or in component source wafer 20 in step 101. Each micro-transfer printable component 22 comprises a device 82 and an ablation layer 50 disposed on, over, on a side of, or in each component 22. Ablation layer 50 can be disposed on a side of device 82 or can be disposed between an encapsulation layer 80 and device 82. In step 110, a stamp 10 comprising a body 12 and spaced-apart posts 14 protruding away from body 12 is provided. Posts 14 have a spatial distribution on body 12 matched to a spatial distribution of micro-transfer printable components 22 on or in component source wafer 20. In step 120 a light source 30 is provided and in step 130 a destination substrate 70 is provided. In step 150 each post 14 is contacted to a micro-transfer-printable component 22 and removed from component source wafer 20 with the adhered micro-transfer printable components 22 forming adhered components 22. In step 191, adhered components 22 are disposed adjacent to or in contact with and in alignment with destination substrate 70. In step 162, one or more of posts 14 and ablation layer 50 of adhered component 22 adhered to each of the one or more posts 14 is irradiated with electromagnetic radiation to ablate ablative material 52 and stamp 10 is removed (in the same or different steps) to detach component 22 from post 14, leaving components 22 in contact with destination substrate 70. The irradiation can be a flood exposure that irradiates all of the posts 14 or a selective irradiation that irradiates only posts 14 or only selected posts 15. The irradiation can also be patterned or unpatterned with respect to each post 14 (e.g., each selected post 15). Optionally, in step 162 stamp 10 is removed with a portion of encapsulation layer 80. In optional step 210, post 14 is cleaned. If no more components 22 are to be printed, the process is done, but if more components 22 are to be printed, the process can return to step 162 to print further sets of components 22 already adhered to posts 14 or to step 150 to pick up and print further sets of components 22. Some embodiments can comprise patterning the electromagnetic radiation emitted by light source 30.

In some embodiments, posts 14 are spaced apart, for example in an array and destination substrate 70 can comprise one or more layers and have a receiving surface.

In some embodiments, component source wafer 20 comprises a patterned sacrificial layer 66 defining spaced-apart sacrificial portions 68 and anchors 64, and the micro-transfer printable components 22 are each disposed over a sacrificial portion 68 and physically connected to an anchor 64 by a tether 62 (e.g., one or more tethers 62 to each of one or more anchors 64). The steps of contacting posts 14 to the micro-transfer printable components 22 and removing stamp 10 breaks (e.g., fractures) or separates tethers 62 (forming broken (e.g., fractured) or separated tethers 63) or separates tethers 62 from the micro-transfer printable components 22.

Some methods of the present disclosure can comprise physically contacting components 22 to destination substrate 70 using stamp 10. The step of irradiating the one or more of the posts 14 can be performed at least partially at the same time as removing stamp 10 from destination substrate 70. Methods of the present disclosure can comprise cleaning the one or more of the posts 14 after removing stamp 10.

In some embodiments of the present disclosure, stamp 10 is aligned with destination substrate 70 at a first position and methods of the present disclosure comprise moving stamp 10 to a second position in alignment with destination substrate 70 different from the first position after removing stamp 10. One or more of posts 14 can be a first subset of posts 14 and a second subset can comprise one or more of posts 14 different from the first subset of posts 14. Methods can comprise irradiating posts 14 of the second subset and ablation layer 50 of the micro-transfer printable component 22 adhered to each of posts 14 of the second subset with light source 30 to detach component 22 from post 14. This step can be performed without picking up a new set of micro-transferable components 22 from component source wafer 20 (e.g., performing step 162 after step 230 or step 210). In some embodiments, a second subset of components 22 are picked up from component source wafer 20 (e.g., performing step 150 after step 230 or step 210).

In some embodiments, alignment with destination substrate 70 is a first alignment and components 22 detached from posts 14 are first components 22. Some methods of the present disclosure can comprise contacting each post 14 to a second micro-transfer printable component 22 of the micro-transfer printable components 22 different from any of the first components 22 to adhere the second micro-transfer printable component 22 to post 14, forming adhered second components 22. Stamp 10 and adhered second components 22 are disposed in a second alignment with destination substrate 70 different from the first alignment. One or more of posts 14 and ablation layer 50 of the adhered second component 22 can be irradiated with light source 30 to detach the second component 22 from post 14. Stamp 10 can be removed from destination substrate 70.

As illustrated in FIG. 22, in some embodiments, a printable component 22 can have an unpatterned layer 50 of ablative material 52 disposed on device 82. As shown in FIG. 23, in some embodiments, a printable component 22 can have a patterned layer 50 of ablative material 52 disposed on device 82. By controlling the amount and location of ablative material 52 on printable component 22, the location and energy generated by ablation can be correspondingly controlled, improving component 22 transfer accuracy and success.

As shown in the flow diagram of FIG. 24 and illustration of FIG. 25, methods of the present disclosure can comprise picking up an encapsulation layer 80 with posts 14 of stamp 10 from an encapsulation layer source substrate (not shown) in step 151, contacting encapsulation layer 80 to ablative material 52 from an ablative material source substrate (not shown) in step 152, and then contacting the ablative material 52 to components 22 on component source wafer 20 in step 153 (as shown in FIG. 25). Components 22 can then be printed as described above, and post 14 cleaned in step 210. In such embodiments, components 22 do not incorporate ablative material 25; ablative material 52 is external to and deposited on components 22.

The use of ablation in conjunction with transfer printing can increase the energy dissociating a component 22 from a post 14. The increased energy can obviate the need to use other methods to enhance component 22 separation from post 14. For example, a shear translation of stamp 10 horizontally and parallel to destination substrate 70 is, in some embodiments, not necessary where such a translation could have been otherwise necessary for successful printing. This, in turn, can increase the accuracy with which component 22 is positioned on destination substrate 70 (e.g., enabling micron or sub-micron accuracy).

Destination substrate **70** can be any suitable substrate to which components **22** can be transferred (e.g., micro-transfer printed), for example glass, plastic, ceramic, sapphire, semiconductor, or quartz. Substrates found in the display industry are suitable and can be commercially obtained. Destination substrate **70** can have a layer **72** of adhesive provided on a surface of a substrate material, for example an epoxy, resin, adhesive, or polymer layer provided on a glass or plastic substrate material, for example SU-8. Adhesive layer **72** can assist in adhering components **22** transferred to destination substrate **70** and can be selected to facilitate 5
adhesion given the material qualities and surface energies of components **22** and stamp **10**. Adhesive layer **72** can be patterned (e.g., disposed only in desired locations corresponding to desired locations for components **22**).

Exemplary micro-transfer printing methods for transferring active components **22** from one substrate to another are described in U.S. Pat. No. 8,889,485, entitled Methods of Surface Attachment of Flipped Active Components, issued Nov. 18, 2014. Micro-transfer printing processes suitable for disposing components **22** onto destination substrates **70** are described in Inorganic light-emitting diode displays using micro-transfer printing (Journal of the Society for Information Display, 2017, DOI #10.1002/jsid.610, 1071-0922/17/2510-0610, pages 589-609), U.S. Pat. No. 8,722,458 entitled Optical Systems Fabricated by Printing-Based Assembly, U.S. patent application Ser. No. 15/461,703 entitled Pressure Activated Electrical Interconnection by Micro-Transfer Printing, U.S. patent application Ser. No. 14/822,864 entitled Chipllets with Connection Posts, U.S. patent application Ser. No. 14/743,788 entitled Micro-Assembled LED Displays and Lighting Elements, and U.S. patent application Ser. No. 15/373,865, entitled Micro-Transfer Printable LED Component, the disclosure of each of which is incorporated herein by reference in its entirety.

According to various embodiments of the present disclosure, component source wafer **20** can be provided with components **22**, release layer, and tethers already formed, or they can be constructed as part of a method in accordance with certain embodiments of the present disclosure. Component source wafer **20** and micro-transfer printable components **22**, stamp **10**, and destination substrate **70** can be made separately and at different times or in different temporal orders or locations and provided in various process states.

Methods disclosed herein can be iteratively applied to a single or multiple destination substrates **70**. By repeatedly transferring sub-arrays of micro-transfer printable components **22** from a component source wafer **20** to a destination substrate **70** with a stamp **10** and relatively moving stamp **10** and destination substrate **70** between stamping operations by a distance equal to the spacing of selected micro-transfer printable components **22** in the transferred sub-array between each transfer of micro-transfer printable components **22**, an array of micro-transfer printable components **22** formed at a high density on a component source wafer **20** can be transferred to a destination substrate **70** at a much lower density. In practice, component source wafer **20** is likely to be expensive, and forming micro-transfer printable components **22** with a high density on component source wafer **20** will reduce the cost of micro-transfer printable components **22**, especially as compared to forming circuits on destination substrate **70**. Transferring micro-transfer printable components **22** to a lower-density destination substrate **70** can be used, for example, if micro-transfer printable components **22** include components **22** that manage elements (e.g., are controllers) distributed over destina-

tion substrate **70**, for example in a display, digital radiographic plate, or photovoltaic system. Moreover, in some embodiments, not every post **14** of a stamp **10** is contacted to a component **22** during a transfer printing operation.

In some embodiments, a component **22** is an active micro-transfer printable device that is an integrated circuit formed in a crystalline semiconductor material. The integrated circuit can comprise a substrate that provides sufficient cohesion, strength, and flexibility such that it can adhere to destination substrate **70** without breaking as transfer stamp **10** is removed.

In comparison to thin-film manufacturing methods, using densely populated component source wafers **20** and transferring functional micro-transfer printable components **22** to a destination substrate **70** that requires only a sparse array of micro-transfer printable components **22** located thereon does not waste or require active layer material on a destination substrate **70**. Components **22** can be made with crystalline semiconductor materials that have higher performance than thin-film active circuits. Furthermore, the flatness, smoothness, chemical stability, and heat stability requirements for a destination substrate **70** used in some embodiments of the present disclosure may be reduced because the adhesion and transfer process is not substantially limited by the material properties of destination substrate **70**. Manufacturing and material costs may be reduced because of high utilization rates of more expensive materials (e.g., component source wafer **20**) and reduced material and processing requirements for destination substrate **70**.

Certain embodiments of the present disclosure provide micro-transfer printed substrates populated with only known-good components **22** with improved yields and reduced manufacturing costs. For example, destination substrate **70** can be a display substrate and components **22** can be inorganic light-emitting diodes (LEDs) in a display made at least partly by micro-transfer printing. Ablation layer **50**, when and where present, facilitates detaching selected components **23** from distal ends **18** of posts **14** of stamp **10**; a substantially transparent ablation layer **50** enables light emitted from the inorganic light-emitting diodes to pass through the ablation layer **50**, enabling a display that emits light in a direction away from the display substrate.

As is understood by those skilled in the art, the terms “over” and “under” are relative terms and can be interchanged in reference to different orientations of the layers, elements, and substrates included in the present disclosure. For example, a first layer on a second layer, in some implementations means a first layer directly on and in contact with a second layer. In other implementations a first layer on a second layer includes a first layer and a second layer with another layer therebetween.

Throughout the description, where apparatus and systems are described as having, including, or comprising specific components, or where processes and methods are described as having, including, or comprising specific steps, it is contemplated that, additionally, there are apparatus and systems included in the disclosure that consist essentially of, or consist of, the recited components, and that there are processes and methods according to embodiments of the disclosure that consist essentially of, or consist of, the recited processing steps.

It should be understood that the order of steps or order for performing certain action is immaterial so long as operability is maintained. Moreover, two or more steps or actions in some embodiments can be or are conducted simultaneously.

Having described certain implementations of micro-transfer printing systems and methods of their use, it will now

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become apparent to one of skill in the art that other implementations incorporating the concepts of the disclosure may be used. Therefore, the disclosure should not be limited to certain implementations, but rather should be limited only by the spirit and scope of the following claims.

PARTS LIST

10 stamp
 12 body
 14 post
 15 selected post
 16 non-selected post
 18 distal end of post
 20 component source wafer
 22 component
 23 selected component
 24 non-selected component
 26 printed component
 30 light source/laser
 32 light
 34 optics
 36 optical system
 38 optics controller
 39 memory
 40 motion platform
 50 ablation layer/layer of ablative material
 51 portion of ablation layer
 52 ablative material
 62 tether
 63 fractured tether
 64 anchor
 66 patterned sacrificial layer
 68 sacrificial portion
 70 destination substrate
 72 adhesive layer
 74 first locations
 76 second locations
 80 encapsulation layer
 82 device/semiconductor structure
 83 component contact pads
 84 electrode
 87 patterned dielectric layer
 88 encapsulation layer/second dielectric layer
 90 test fixture
 92 printed system
 99 micro-transfer printing system
 100 provide source wafer step
 101 provide source wafer and components with ablation layer step
 110 provide stamp with posts step
 120 provide light source step
 130 provide destination substrate step
 140 test components to determine selected non-functional components step
 141 test components to determine selected functional components step
 150 contact posts to component step
 151 contact posts to encapsulation layer step
 152 contact encapsulation layer to ablative material step
 153 contact ablative material to component step
 155 optional remove stamp from source wafer step
 160 irradiate selected posts and detach selected components step
 162 irradiate selected posts and remove stamp to detach selected components step

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170 optional examine selected posts for selected components step
 180 optional determine selected components remaining on selected posts step
 5 190 print non-selected components to destination substrate step
 191 move components to destination substrate step
 195 select component subset step
 10 200 remove stamp from destination substrate with no components step
 201 remove stamp from destination substrate with non-selected components step
 205 move stamp with respect to destination substrate step
 15 210 clean stamp step
 220 determine missing component test step
 230 done step

What is claimed:

20 1. A method of micro-transfer printing, comprising:
 providing a component source wafer having micro-transfer printable components disposed on or in the component source wafer, each micro-transfer printable component comprising a device and an ablation layer
 25 disposed on the device;
 providing a stamp comprising a body and spaced-apart posts protruding away from the body, the posts having a spatial distribution on the body matched to a spatial distribution of ones of the micro-transfer printable components on or in the component source wafer;
 30 providing a light source;
 providing a destination substrate;
 contacting each of the posts to a micro-transfer printable component of the micro-transfer printable components
 35 to adhere the micro-transfer printable component to the post, thereby forming adhered micro-transfer printable components;
 removing the stamp with the adhered micro-transfer printable components from the component source wafer;
 40 disposing the stamp with the adhered micro-transfer printable components in alignment with the destination substrate;
 irradiating one or more of the posts and the ablation layer
 45 of the micro-transfer printable component adhered to each of the one or more of the posts with light from the light source to detach the micro-transfer printable component from the post, thereby forming one or more detached micro-transfer printable components; and
 removing the stamp from the destination substrate, leaving the one or more detached micro-transfer printable components in contact with the destination substrate,
 wherein the body and the posts are substantially transparent to the light.
 50 2. The method of claim 1, wherein the component source wafer comprises a patterned sacrificial layer defining spaced-apart sacrificial portions and anchors, and the micro-transfer printable components are each disposed over one of the sacrificial portions and physically connected to one of the anchors by a tether, and wherein the steps of contacting
 55 each of the posts to the micro-transfer printable component and removing the stamp fractures or separates the tether thereby separating the adhered micro-transfer printable components from the source wafer.
 60 3. The method of claim 1, comprising physically contacting the adhered micro-transfer printable components to the destination substrate using the stamp.
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4. The method of claim 1, wherein the step of irradiating the one or more of the posts is performed at least partially at the same time as removing the stamp from the destination substrate.

5. The method of claim 1, wherein the stamp is aligned with the destination substrate at a first position and the method comprises moving the stamp to a second position in alignment with the destination substrate different from the first position after removing the stamp.

6. The method of claim 5, wherein the one or more of the posts is a first subset of the posts and a second subset of the posts comprises one or more of the posts different from the first subset of the posts and the method comprises irradiating the second subset of the posts and the ablation layer of the micro-transfer printable component adhered to each of the second subset of the posts with second light from the light source to detach the micro-transfer printable component from the post.

7. The method of claim 1, wherein the alignment with the destination substrate is a first alignment and the one or more detached micro-transfer printable components are one or more first components, and the method comprises contacting each of the posts to a second micro-transfer printable component of the micro-transfer printable components different from any of the first micro-transfer printable components to adhere the second micro-transfer printable component to the post, thereby forming adhered second micro-transfer printable components;

removing the stamp with the adhered second micro-transfer printable components from the component source wafer;

disposing the stamp with the adhered second micro-transfer printable components in a second alignment with the destination substrate different from the first alignment;

irradiating one or more of the posts and the ablation layer of the second micro-transfer printable component adhered to the one or more of the posts with second light from the light source to detach the second micro-transfer printable component from the post; and
removing the stamp from the destination substrate.

8. The method of claim 1, wherein the ablation layer is a patterned ablation layer.

9. The method of claim 1, wherein the micro-transfer printable components each comprise an individual encapsulation layer covering the ablation layer and irradiating the one or more of the posts vaporizes at least a portion of the ablation layer thereby detaching the micro-transfer printable component adhered to each of the one or more of the posts.

10. The method of claim 9, wherein removing the stamp occurs at a sufficient rate such that at least a portion of the encapsulation layer remains adhered to each of the one or more of the posts.

11. The method of claim 10, comprising cleaning the at least a portion of the encapsulation layer remaining from each of the one or more of the posts.

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12. The method of claim 1, comprising disposing the ablation layer on the device of each of the micro-transfer printable components in a common patterned deposition.

13. The method of claim 1, comprising testing each of the components before forming the adhered micro-transfer printable components to determine one or more faulty components, wherein the adhered micro-transfer printable components comprise the one or more faulty components and the irradiating does not irradiate any post of the posts that is adhered to one of the one or more faulty components.

14. The method of claim 1, comprising testing each of the components before forming the adhered micro-transfer printable components to determine one or more non-faulty components, wherein the adhered micro-transfer printable components comprise the one or more non-faulty components and the irradiating comprises irradiating only each post of the posts that is adhered to one of the one or more non-faulty components and the ablation layer of the one of the one or more non-faulty components.

15. The method of claim 1, comprising:

providing a disposal area;

moving the stamp to the disposal area before the irradiating of the one or more of the posts; and

disposing one or more of the micro-transfer printable components in the disposal area by irradiating each of the posts adhered to the one or more of the micro-transfer printable components and the ablation layer of the one or more of the micro-transfer printable components.

16. The method of claim 1, wherein the irradiating of the one or more of the posts comprises irradiating a single post at a time.

17. The method of claim 1, wherein the irradiating of the one or more of the posts comprises irradiating multiple posts at a time.

18. The method of claim 1, wherein each of the posts has a distal end away from the body and the step of contacting each of the posts to a micro-transfer printable component comprises contacting the distal end of the post to the micro-transfer printable component to adhere the micro-transfer printable component to the distal end of the post, and

wherein the irradiating of the one or more of the posts with the light source irradiates the distal end of each post of the one or more of the posts to detach the micro-transfer printable component adhered to the post from the distal end of the post.

19. The method of claim 1, comprising:

testing each of the micro-transfer printable components before forming the adhered micro-transfer printable components to determine faulty components; and
providing a mapping of the faulty components.

20. The method of claim 1, comprising cleaning the one or more of the posts after removing the stamp.

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